The Role of Hearing Sensitivity above 8 kHz in Auditory Localization

Sarah Elizabeth Gray

A thesis submitted in partial fulfilment of the

requirements for the Degree of

Master of Audiology

Department of Communication Disorders

University of Canterbury, Christchurch,

New Zealand.

May 2014

Contents

Acknowledgements

There are many people whom I wish to thank who have provided much guidance and support in the production and final completion of this project. Firstly, my very patient and talented supervisors, Dr Gregory O'Beirne and Melissa Babbage.

Thank you to Prof. Simon Carlile (Department of Physiology), University of Sydney who so generously provided the female voice recordings.

To Don Sinex, University of Canterbury who provided great advice and also helped create sound stimuli.

To Emily Lin who was so helpful and patient when I was wading through the statistical analysis.

Thank you to the many participants who willingly took the time to have their hearing tested and participate in the localization task.

To my awesome MAUD classmates who I feel privileged to have spent time with over the last few years.

A big thank you to my mother who helped out with cooking and childcare when there were deadlines, and to my father who allowed her to do so.

Last but not least to my wonderful husband Blair who supported me in so many ways, and my beautiful three girls Rebekah, Emma and Katie.

Abstract

The ability to identify where sound is coming from is required for everyday listening tasks such as identifying in which direction the phone is ringing and to help locate who is calling your name in a social situation. While this localization ability has been found to be reduced in listeners with a hearing loss in the typically measured frequency range of 250 to 8000 kHz, less is known about listeners who have a hearing loss that is mainly limited to the extended high frequencies of 8 to 14 kHz, particularly when abilities are tested with speech stimuli. The purpose of the current study was to determine whether listeners with a hearing impairment at these higher frequencies performed less accurately in a number of localization tasks.

Twenty-three participants with normal hearing (thresholds not exceeding 20 dB HL from 250 to 14 kHz) and 23 participants with normal hearing up to and including 3 kHz and with at least a moderate hearing loss in the extended high frequencies (thresholds reaching at least 55 dB HL in any of the frequencies from 8 kHz to 14 kHz), localized noise and speech stimuli at a level of 75 dBA in a free field situation. Thirteen speakers were used in four different speaker arrangements; the frontal horizontal plane, lateral horizontal plane, frontal vertical plane and lateral vertical plane. The noise stimuli included noise band-passed filtered between 300 Hz and 16 kHz, and 300 Hz and 8 kHz. Speech stimuli were individual words with strong amounts of high frequency content above 8 kHz and weak amounts of high frequency content above 8 kHz. The two types of speech stimuli were also band-passed filtered using the same filter cut-off frequencies as the noise stimuli.

No significant main effect differences were found between the localization ability of the two hearing groups for any of the four experiments. However, within experiment analysis revealed in the lateral vertical plane the normal hearing group localized significantly better than the hearing loss group for both the strong and weak stimuli. Significant differences were also found across experiments with both groups of participants localizing more accurately in the frontal horizontal plane and worst in the frontal vertical plane. All participants were found to localize significantly better with the greater bandwidth of 300 Hz to 16 kHz, and also for both types of speech stimuli when compared to the noise stimuli,

although post hoc analysis found that these differences were not consistent between all speaker locations.

List of Tables

List of Figures

Introduction

Localization of sound is a basic function of the auditory system used by animals to identify the position of a predators prey and mates in order to behave appropriately (Pickles, 1988). In humans, having an awareness of their environment and orientation in space is essential for safety; for example the ability to locate a bus that is out of sight but getting closer. Localization is also important for everyday tasks such as identifying in which direction the telephone is ringing and for social situations to help locate a friend who is calling you.

Several researchers have indicated that a sensorineural and/or conductive hearing loss in the typically measured audiological frequencies of 250 to 8 kHz can disrupt these localization abilities (Abel, Giguere, Consoli, & Papsin, 2000; Akeroyd & Guy, 2011; Gabriel, Koehnke, & Colburn, 1992; Noble, Byrne, & Lepage, 1994; Smith-Olinde, Koehnke, & Besing, 1998). Localization abilities may also be disrupted when hearing loss is limited in this conventionally tested frequency range, but greater above 8 kHz. Listeners with a hearing loss that is minimal below approximately 4 kHz, and greatest in the 'extended high-frequency range' (EHFs) from 8 to 16 kHz, have also shown impaired localization performance with noise stimuli (Dobreva, O'Neill & Paige, 2011; Otte et al., 2013); however, whether this phenomenon also occurs when speech stimuli are used has not been researched as extensively.

The overall aim of this thesis is therefore to address this gap in the literature by investigating the contribution of spectral content above 8 kHz to the localization of noise and speech stimuli. This introductory chapter briefly describes the structure and function of the cochlea and changes in the perception of sounds that can occur as a result of sensorineural hearing loss. Information will be provided about the current applications of EHF audiometry, along with a description of localization processes. It will conclude with the goals and hypotheses of the current study.

1.1 The Cochlea

The human peripheral auditory system is comprised of outer, middle and inner components, which are illustrated in Figure 1. The outer ear or pinna directs sound into the middle ear; an air filled cavity containing three small bones called the malleus, incus and stapes along with a number of other structures. These bones, termed the ossicles, form a chain, and perform impedance matching by transferring energy from sound waves to fluids of the inner ear (Musiek & Baran, 2007). The inner ear consists of two structures; the vestibular system and the cochlea. The vestibular system, containing three semi-circular canals and two otolithic organs, is responsible for maintaining balance, whereas the cochlea is essential for hearing (Taylor & Mueller, 2011).

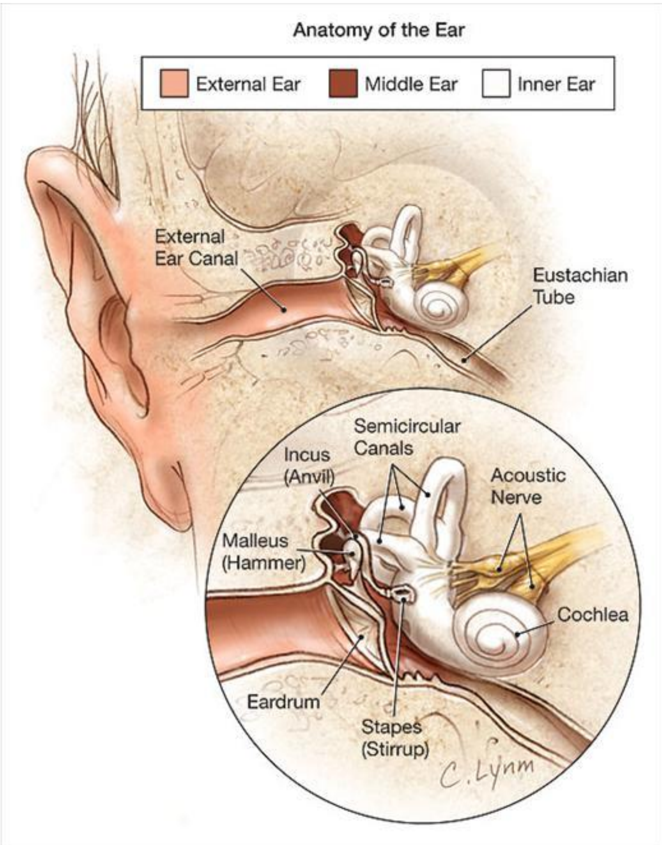
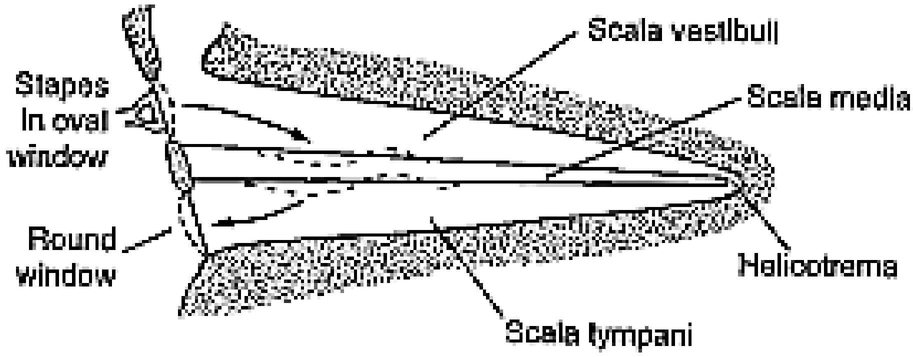


Figure 1. Illustration of the peripheral auditory system (from Parmet, 2007).

The cochlea is shaped like a spiral shell, and when uncoiled is approximately 34 mm in length (Ashmore, 2008). It is divided into three chambers, namely, the scala vestibuli, the scala media and the scala tympani. The top chamber scala vestibuli is connected to the middle ear via the oval window, whereas the bottom chamber, the scala tympani, begins at the round window and ends at the helicotrema (Slepecky, 1996). The middle chamber, scala media, is bordered by Reissner’s membrane at the top and the basilar membrane at the bottom, and provides a specialised ionic environment essential for the mechanotransducing membranes of the sensory hair cells (Ashmore, 2008). Scala media contains the sensory inner and outer hair cells of the Organ of Corti. The unrolled cochlea and structures can be seen in Figure 2.



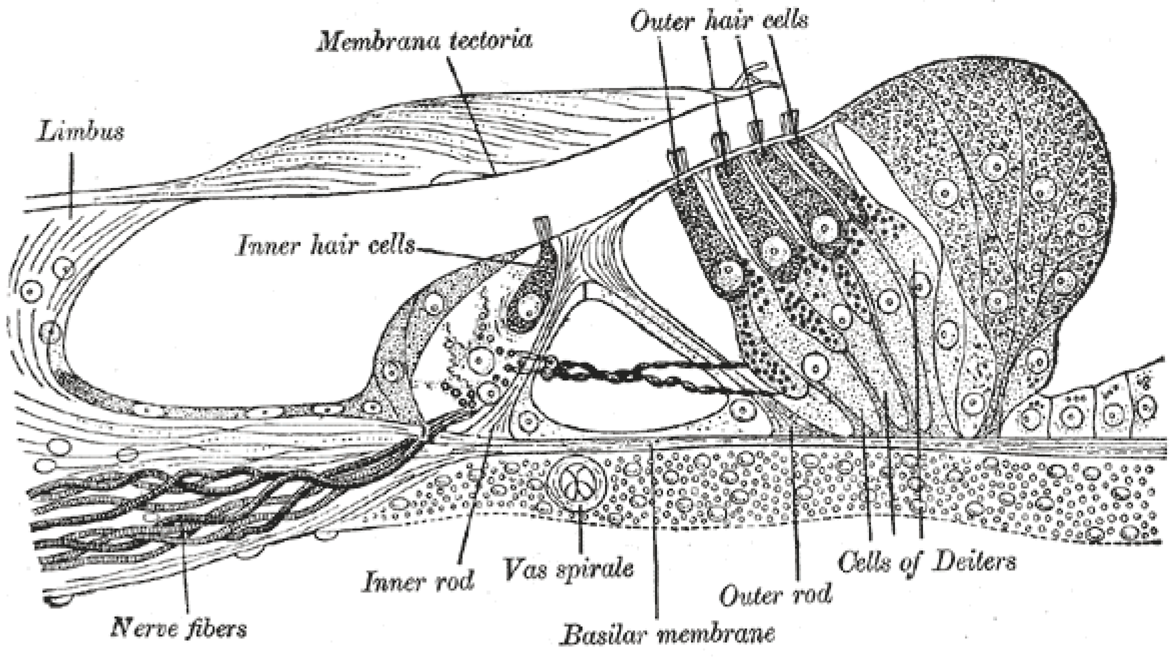


Figure 2. An unrolled cochlea and cross section of the Organ of Corti with the hair cells on the basilar membrane (from Pickles (2008) and Warren (2000)).

Within the cochlea, in response to incoming sound, there is movement of fluid in the chambers as a result of the oval window being pushed inward by the movement of the stapes footplate and the round window bulging outwards (Venema, 2006). The movement of the fluid creates a travelling wave along the basilar membrane, which is narrow and stiff at the basal end, and therefore suited to resonating at higher frequencies, compared to the apical end which resonates at lower frequencies due to its wide, compliant properties. The result is that different frequencies (seen in Figure 3) are represented along the basilar membrane at different places, resonating maximally at specific points depending upon the frequencies of the incoming sounds (Taylor & Mueller, 2011).

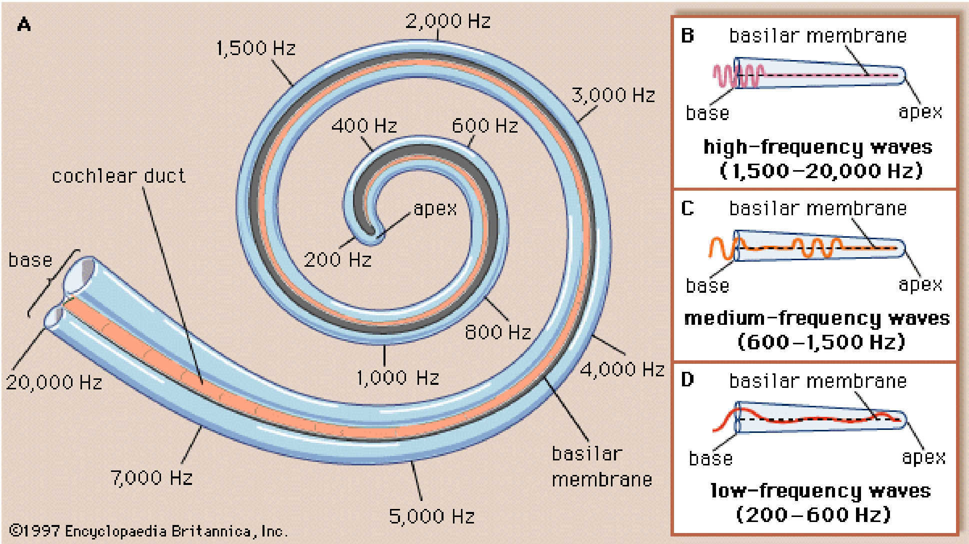


Figure 3. A diagram of an unrolled cochlea showing the different frequencies in the cochlea. The base is more suited to resonating at higher frequencies whereas towards the apex the lower frequencies resonate (from Encyclopedia Britannica, 1997).

The role of the inner hair cells is to convert the motion of the basilar membrane into neural signals. As the basilar membrane moves, the hair cells follow the motion and via a process that causes voltage fluctuations, the release of transmitter causes the stimulation of afferent auditory neurons that are aligned to the resonant frequency, the result being the maintenance of the frequency code of the basilar membrane. The brain then codes these neural patterns as changes in intensity and frequency (Taylor & Mueller, 2011). The outer hair cells contribute to this process by enhancing the movement of the basilar membrane- especially for softer sounds of approximately 40 to 60 dB (Ashmore, 2008).

1.2 Sensorineural Hearing Loss

Sensorineural hearing loss is a common type of hearing loss that is caused by damage to the cochlea and/or neural structures such as the auditory nerve (Moore, 2007). Such hearing loss is acquired, for example, as part of aging, from exposure to loud noise or ototoxic drugs, or can be due to genetic factors (Angeli, 2005). While this type of hearing loss can involve structures outside the cochlea; it is common for the damage to occur to the hair cells within the cochlea (Moore, 2007). In most cases of sensorineural hearing loss damage and distortion to the hair cells occurs; especially to the stereocilia (which are finger like extensions of the cells), and their associated tip and cross links (Slepecky, 1996). In some instances entire hair cells may die (Moore, 2007). Damage to the outer hair cells, typically occurs first, causing a mild to moderate hearing loss, followed by a more significant hearing loss when there is additional destruction of the inner hair cells (Venema, 2006). Figure 4 illustrates both normal and damaged hair cells. In some instances, with particularly severe hearing loss, there may be cochlear dead regions where there are very few or no functioning hair cells and /or neurons. This leads to "off frequency" listening whereby hearing occurs by way of remote hair cells that are located on a part of the basilar membrane that is representative of a different frequency (Moore, 2007).

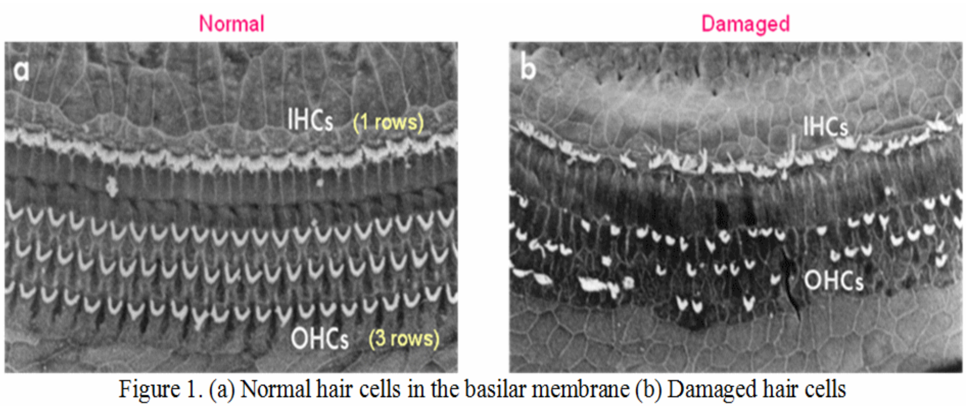


Figure 4. Scanning electron micrographs of (a) normal and (b) damaged cochlear sensory cells (from Ryan, 2000).

In sensorineural hearing loss, along with reduced hearing sensitivity, damage to the sensory hair cells may also cause a reduction in frequency selectivity. (Moore, 1985). This refers to the ability of the auditory system to separate different components of a sound and can cause difficulties with perceiving speech and binaural localization of sound in space (Smith-Olinde et al., 1998). A reduction in selectivity can be illustrated by looking at a tuning curve (Figure 5), which was measured from the basal end of a guinea pigs cochlea (Yates, Johnstone, Patuzzi, & Robertson, 1992). While this curve measures how large an input is required to elicit a given output level as a function of frequency, and therefore the sensitivity at that frequency, it also shows how damaged hair cells can change the shape of the curve and cause a sharp peak to become flattened. As a consequence of a flatter tuning curve more of the basilar membrane is stimulated, leading to the listener having less ability to distinguish between frequencies that are close together (Venema, 2006).

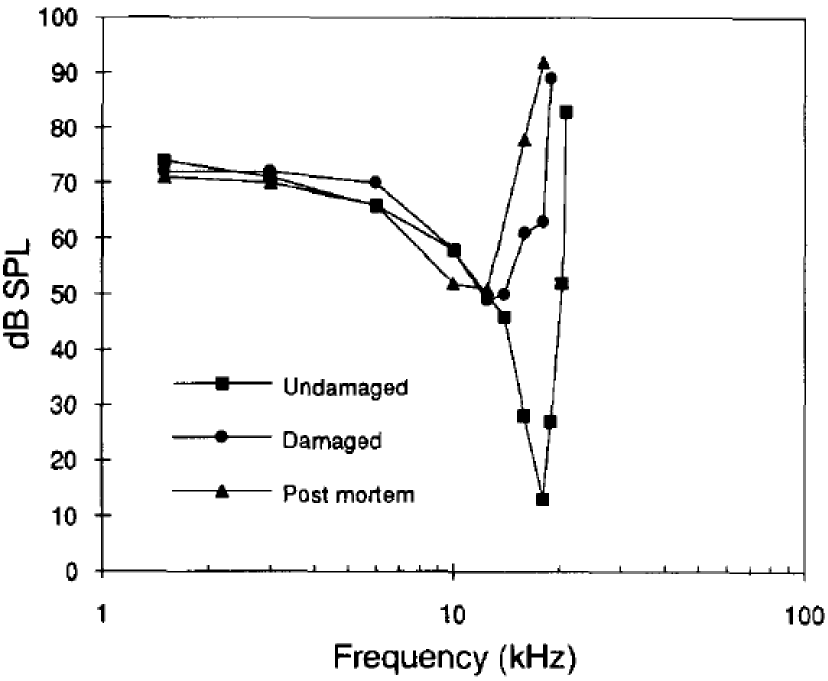


Figure 5. Basilar membrane frequency curve showing the sound pressure required for vibrating a certain place along the basilar membrane. It shows the greatest sensitivity at a frequency of 10.9 kHz and therefore less of an input level is required to vibrate that area of the cochlea compared to lower frequencies. The squares are measurements of the cochlea in good condition in comparison to the circles which indicate a damaged cochlea and a flatter curve (from Yates et al., 1992).

A decrease in temporal resolution is also associated with sensorineural hearing loss and refers to the ability of the listener to follow changes in the time pattern of sounds (Moore, 1985). Numerous techniques have been used to estimate temporal resolution; for example gap detection, where it is generally found that participants with a sensorineural hearing loss require a larger gap threshold when listening for a gap within a signal compared to normal hearing participants (Moore, Shailer, & Schooneveldt, 1992). The reduction of this temporal ability is thought to potentially cause difficulties in the processing of directional information which has come from the filtering of the spectra by the pinna and therefore can affect the ability to localize sound. The loss of either or both of temporal and frequency resolution that may accompany a sensorineural hearing loss in any frequency range may therefore have implications for a listener's ability to localize sounds.

1.3 Extended High Frequency Audiometry

The upper frequency limit heard by humans is generally accepted to be 20 kHz (Sakamoto, Sugasawa, Kaga, & Kamio, 1998). However, threshold measurements in the EHF's have been found to be more variable as the frequency gets higher, particularly above 16 kHz, and therefore audiometric thresholds are typically not assessed above 16 kHz (Ashihara, 2007; Schmuziger, Probst & Smurzynski, 2004). Threshold deterioration associated with the aging cochlea is typically first evident within the EHF range (Ahmed et al., 2001; Hallmo, Sundby, & Mair, 1994; Lee et al., 2012; Wiley et al., 1998). This is as a consequence of more severe degeneration of structures in the basal turn of the cochlea (Sakamoto et al., 1998). As a consequence of the numbers of non-responders at these extended frequencies, the usefulness of EHF audiometry can become limited in older adults (Hallmo et al., 1993).

In the past there have been concerns around the reliability of extended high frequency testing due to issues such as standing waves and equipment limitations producing low frequency noise at high presentation levels (Schmuziger et al., 2007; Schmuzinger et al., 2004). However, these issues have been overcome and the test-retest reliability of pure tones from 8 to 14 kHz with Sennheiser HAD 200 headphones and Etymotic Research (ER

2) earphones have been found to be within a clinically acceptable range of + or – 10 dB when testing healthy subjects (Frank, 2001; Schmuziger et al., 2004). Sixteen kHz is also often tested, although Schmuziger et al., (2004) reports that measurements should be treated cautiously due to decreased test-retest reliability.

High frequency audiometry is already successfully used in a number of clinical situations. The most common is the monitoring of auditory function in patients who are taking doses of ototoxic drugs such as cisplatin, as it has been found that threshold shifts in the EHF's are more sensitive to changes than pure tone results at the lower frequencies (Arora et al., 2009; Dreschler, Vanderhulst, Tange & Urbanus, 1989; Weissenstein, Deuster, Knief, Zehnhoff-Dinnesen & Schmidt, 2012). In some studies the EHF's have also been found to be more sensitive to noise exposure than the lower frequencies (Ahmed et al., 2001; Mehrparvar, Mirohammadi, Ghoreyshi, Mollasadeghi, & Loukzadeh, 2011; Somma et al., 2007; Wang et al., 2000). However, such findings are not consistent across all studies (Balatsouras, Homsioglou, & Danielidis, 2005). People with significant tinnitus have also been found to have degradation in the EHF's, despite normal thresholds at lower frequencies, and in these circumstances clinical EHF testing has been suggested (Shim et al., 2009; Yildirim, Berkiten, Kuzdere, & Ugras, 2010). Although a wealth of research has investigated EHF thresholds across different populations, there does not appear to be any studies that have attempted to correlate the presence or degree of hearing loss in this frequency range with any aspect of auditory performance.

1.4 Localization

For localization, the auditory system relies on a number of binaural cues including inter-aural time/phase differences (ITDs) and/or level differences (ILDs) that come about as a result of the separation of the two ears in space. Monaural spatial cues are also employed and are the result of direction dependant interaction between the incoming sound wave and the upper torso, shoulders, head and pinna, which have the effect of filtering and varying the spectral content of the sound (Blauert, 1997). The spectral pattern created by this filtering can then be used by the listener to help judge location and overcome ambiguities of the auditory system (Moore, 2007). These cues are utilised to a greater extent at different frequencies. This will be discussed below. Another important cue for localization can come from head movement, which contributes to location perception only if the stimuli is of a long enough duration (Perrett & Noble, 1997). The present study was focused towards investigating the role of spectral content in localization, irrespective of stimulus duration. For this reason participants were not permitted to move their heads during testing to eliminate any potential contribution of the head movement cue to localization of the stimulus.

There is a significant amount of literature on localization using a variety of methodologies to clarify the role of different cues in overall performance. Many of the studies use virtual stimuli in order to have greater control over stimulus (Best, Carlile, Jin & Schaik, 2005; Macpherson & Sabin, 2013; Zhang & Hartmann, 2010) along with sophisticated equipment such as robotic arms and large circular spheres to ensure accuracy of results (Brungart & Simpson, 2009; Gilkey & Anderson, 1995; Otte et al., 2013). Filtered noise or frequency bands varying in bandwidth and centre frequency are also traditionally used as stimuli (Langendijk & Bronkhorst, 2002; Middlebrooks, 1992; Yost, Loiselle, Dorman, & Burns, 2013). A number of studies have also used speech stimuli due to its importance for communication (Best at el 2005., Giley & Anderson, 1995., Karlsen, 1999). Speech as a stimulus is thought to potentially pose more challenges to the auditory system due to natural spectral fluctuations (Best et al., 2005). The purpose of the current study was to look at the importance of the frequencies 8 kHz and above for localization accuracy in the horizontal and vertical planes. Therefore, studies regarding the various cues required for localization in these planes will be discussed along with the associated errors that come from limiting the frequency content of the stimuli.

1.4.1 Binaural cues

Illustrated simply, ITD cues (illustrated in Figure 6 - left), occur due to sound reaching one ear before reaching the other ear. This cue is mainly found to be dominant in the horizontal plane at frequencies lower than 1.5 to 2 kHz (Carlile et al., 1999; Wightman & Kistler, 1992), due to phase locking of neural fibres, particularly in the case of pure tones (Moore, 2007). However, it has been found that ITDs have been extracted from the envelope of complex high frequency signals (Bernstein & Trahiotis, 2002; Middlebrooks & Green, 1990) so in some circumstances spectral content and hearing sensitivity above 2 kHz may have some influence on the use of ITD cues for localization. ILD cues occur due to sound reaching one ear being less intense than sound reaching the other and this has been labelled the 'head shadow' effect (Moore, 1997). This is represented in Figure 6 (right) and is considered to be the most dominant binaural localization cue between approximately 1.5 and 6 kHz (Middlebrooks, 1992; Wightman & Kistler, 1992; Yost et al., 2013). At these frequencies the length of the wavelength is short enough compared to the dimensions of the head to cause a 'shadow' which can be as large as 20 dB (Moore, 2007). To the author's knowledge there is no research that directly looks at the relationship of the EHF's to these binaural cues. However, if the information already available is extrapolated across frequencies it would suggest that the use of these cues for frequencies of 8 kHz and above would be negligible.

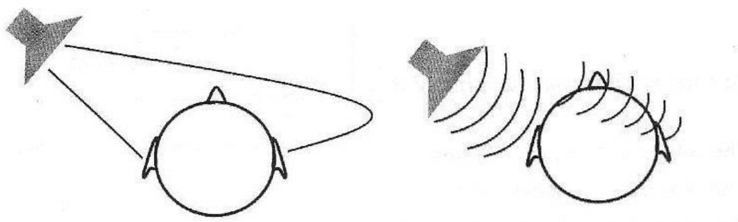


Figure 6. A representation of the ITD binaural cue showing how sound reaches the nearest ear first (left) and the ILD cue where the difference in sound level to the ear is created by the shadow of the head (right) (adapted from Starkey Research, 2008).

1.4.2 Pinna cues

The filtering by the pinna has been termed the head-related transfer function (HRTF) and is unique for each sound source location in space relative to the position of the listener (Blauert, 1997). The consequence of the acoustic stimuli interacting with the head and geometry of the pinna is that a pattern of peaks and notches are created that are individual to each listener. As the wavelength needs to be short enough to cause this interaction effect it is reported that frequencies above 6 kHz are particularly important

(Moore, 2007). A picture of three individual transfer functions is illustrated in Figure 7 to a broadband noise stimuli filtered between 0.5 and 20 kHz. It can be seen that spectral content above 8 kHz causes a number of notches that would be unavailable to the listener if the frequency content was more limited (Otte et al., 2013). The illustration also shows how the transfer function can be variable among listeners. It is noted that a variation in localization ability is often identified within studies despite the participants being normal hearing listeners (Best et al., 2005; Carlile et al., 1999; King, & Oldfield, 1997; Langendijk, Kistler, & Wightman, 2001; Zhang & Hartmann, 2010). One reason is likely due to this individualised filtered pattern. In addition, some listeners likely require different amounts of frequency information.

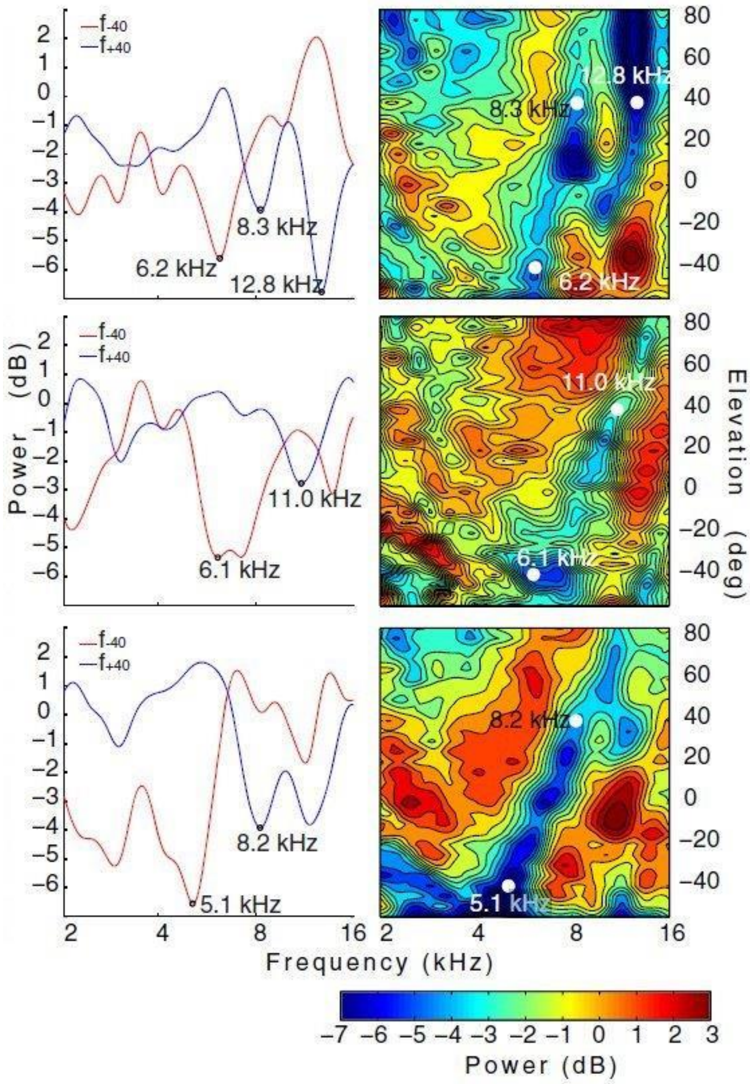


Figure 7. A diagram of the transfer functions on the left and directional transfer functions on the right for three different ears. The transfer functions are at + 40° in elevation (blue line) and 40° in elevation (red line). Characteristic notches can be seen between 5 and 13 kHz (adapted from Otte et al., 2013).

1.4.3 Different frequency bands

As stated, the binaural cues have been found to provide sufficient information for the auditory system to localize in the horizontal plane. A recent study illustrating this is by

Yost, Loiselle, Dorman, & Burns, (2013) who measured the performance in the horizontal plane of 45 normal hearing listeners using 125 to 500, 1500 to 6000, and 125 to 6000 Hz bandwidths with 200 ms noise bursts presented in a sound field with 13 speakers. The assumption was made that these conditions reflected ITD, (125 to 500 Hz) ILD (1500 to 6000 kHz) or ITD and ILD (125 to 6000Hz) cues. No statistical differences were found in reliability/repeatability across the three conditions; although the error was slightly smaller in the broadband condition. The conclusion made was that ILD and ITD cues produce the same level of localization performance and that there is no advantage in having both of the cues available.

However, in the vertical plane, deterioration in localization accuracy comes from the loss of high frequency spectral cues and has also been found to cause reduced accuracy, up/down and front/back errors in studies with reduced frequency content with normal hearing listeners (Best et al., 2005; Brungart & Simpson, 2009; Dobreva, O'Neill & Paige, 2011; King & Oldfield, 1997; Langendijk & Bronkhorst, 2002; Middlebrooks, 1992; Otte et al., 2013; Zhang & Hartmann, 2009). These errors occur as a result of a listener not being able to distinguish between whether a sound comes from behind or in front of them, or above or below them, and is postulated to be as a result of being unable to resolve the 'cone of confusion'. This is illustrated in Figure 8 and can be defined as a set of points at a common lateral angle. If the head is stationary, as in many localization studies, then a given ITD or ILD will not provide enough information for a listener's auditory system to define the position of the sound source in space and therefore further spectral information is required. (Moore, 2007).

While the frequency content required for accurate localization varied amongst studies (due to set up and measurement differences), it has been clearly established that frequencies above 6 kHz and up to 16 kHz are required for accurate vertical localization (Best et al., 2005; Dobreva, O'Neill & Paige, 2011; King & Oldfield, 1997; Langendijk & Bronkhorst, 2002; Middlebrooks, 1992; Otte et al., 2013; Zhang & Hartmann, 2010). One study by Langendijk and Bronkhorst (2002) measured the HRTF of 8 normal hearing listeners and then generated virtual sources and removed cues in the ½, 1 or 2 octave bands in the frequency range above 4 kHz and up to 16 kHz. It was found that spectral information up to 16 kHz was required to correctly localize broadband sounds, and that up-down cues were located mainly in the 6 to 12 kHz band. The researchers also found that for front/back errors localization cues are mainly coded in the band of 8 to 16 kHz.

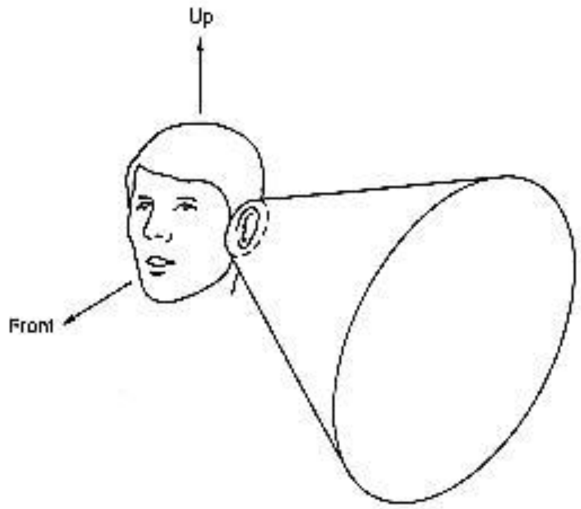


Figure 8. Illustration of the cone of confusion for a specific ITD. All points on the surface of the cone give rise to the same ITD. An example is that if the sound at the left ear is leading that of the right ear, the auditory system recognises that the sound is at the left. In reality however, the sound could be from the front or behind the head, and above or below the horizontal plane. A similar effect occurs for ILDs (from Moore, 2007).

King and Oldfield, (1997) investigated the impact of signal bandwidth on the perception of elevation and front/back for three normal hearing listeners using filtered signals. Participants were presented with signals progressively low passed from low pass 16 kHz to low pass 1 kHz and progressively high-pass filtered from high-pass 1 kHz to high pass 14 kHz from nine different elevation locations. With respect to elevation, the ability to accurately localize occurred when the low pass filter cut off approached 9 kHz and with the high pass condition when the signal band width extended from 6 to 9 to 16 kHz. The ability to distinguish front from back became limited when the low-pass cut off approached 7 to 9 kHz and the high pass approached 10 to 13 kHz.

Zhang and Hartman (2010) specifically examined front/back errors using 11 normal hearing listeners and stimuli with flattened spectra that eliminated spectral cues. Large individual differences were found amongst listeners; however errors were generally found when the spectra was reduced to the range of 6 to 12 kHz for the majority of listeners. There was one exception of a female who required information up to 14 kHz. As a consequence of such studies, it is suggested that listeners who have a hearing loss in the EHF's and therefore have less spectral information to them above 8 kHz, are more likely to localize less accurately in the vertical plane due to the limited EHF content available to them.

1.5 Speech Stimuli

Speech spectral analysis shows that information from speech is mainly found in the frequencies below 8 kHz (Fulop, 2011). However, high frequency audible speech energy has been found above 8 kHz (Monson, Hunter & Story, 2012; Monson, Lotto, & Story, 2012; Moore, Stone, Fullgrabe, Glasberg, & Puria, 2008). Differences in the detection of sustained vowels for singers has even been found between 8 and 16 k Hz (Monson, Lotto, & Ternstrom, 2011).

Research has also show that this energy above 8 kHz does have an impact on perception and intelligibility. For example, Moore & Tan, (2003) found in normal listeners a decrease in perceived sound quality for music signals when the upper cut off was reduced from 16.5kHz, and Stelmachowicz, Pittman, Hoover, and Lewis (2001) found that there was a significant difference in the ability to distinguish /s/ and /z/ by a group of hearing impaired children when their hearing aids were re configured out to 10 kHz from 6kHz. As a consequence of speech content being available above 8 kHz and other auditory processes being significantly impacted by filtering out the higher frequencies it could also be expected that limiting speech content at the EHF's would have an impact on other auditory perception abilities such as localization.

There are a few studies that have looked at the effect of high frequency speech on localization ability (Best et al., 2005; Gilkey & Anderson, 1995). Gilkey & Anderson, (1995) band passed their speech stimuli between 400 Hz and 11 k Hz; while Best et al., (2005) studied the effect of removing the high frequency content of speech stimuli using virtual stimuli for five normal hearing participants in 76 different locations. Best et al., (2005) compared three types of stimuli including broadband noise filtered between 300 and 16 kHz (control), speech low pass filtered between 300 and 8 kHz, and broadband speech filtered between 300 to 16 kHz. Results found that localization in the vertical plane was most accurate in the broadband speech condition, and relatively good in the broadband speech condition. However, in the filtered condition accuracy was reduced, in particular a larger number of errors were made for the low-pass speech condition.

In a second part of their study, Best et al., (2005) attenuated the high frequency information in the speech stimuli above 8 kHz systematically by 20 dB. Results showed that error rate significantly increased as the speech was increasingly attenuated. Therefore, if the assumption is made that filtering out information above 8 kHz acts similarly to a hearing loss in this range due to the spectral information not being transmitted to the brain, than it would be expected that similar results would be found in the EHF loss listeners as found in normal listeners when the EHF information is filtered out.

1.6 Cues Required for Localization in Background Noise

The effect of background noise on the ability to localize is not part of this study and therefore will not be discussed in detail. However, it is important to note that the binaural interactions mentioned above also have the ability to enhance the separation of signals from other stimuli such as noise and speech through the use of these inter-aural differences. This enhancement is due to the already mentioned benefits of the 'head shadow' effect and time differences (Dubno, Ahlstrom, & Horwitz, 2002). As expected, signals are able to be more accurately localized when presented at angles separated from the masker and in better signal to noise ratios (Abouchacra, 1998; Balakrishnan & Freyman, 2008; Kopco, Best & Carlile, 2010).

One study in particular using eight normal hearing participants, showed the effect of high frequency spectral content using cut off frequencies of 1, 2, 4, 6, 8, 10, 12 and 16 kHz for the target and masker and a signal to noise ratio varying from -12 to + 12 dB (Brungart & Simpson, 2009). Results found that in quiet conditions, front back localization required a minimum bandwidth of 10 kHz whereas in noisy conditions with spectral content up to 16 kHz more accurate localization occurred. Vertical localization of many of the participants was also found to be better in quieter conditions when there was frequency content up to 16 kHz; however this was also improved with the presence of high frequency components when a noise masker was present.

1.7 Hearing Impairment on the Ability to Localize

While there is variability amongst listeners, it is has frequently been found that a sensorineural hearing loss at 8 kHz and below has an impact on localization ability and associated activities when measuring inter-aural time and intensity difference effects (Abel, Giguere, Consoli, & Papsin, 2000; Akeroyd & Guy, 2011; Gabriel, et al.,1992; Noble, et al., 1994; Smith-Olinde, et al., 1998). However, to the author's knowledge there are only two studies that have used extended bandwidths and measured EHF thresholds so that extent of hearing loss could be taken into account.

Otte, et al., (2013) studied age related hearing loss and ear morphology with the use of a circular arch presenting 150 ms broadband noise filtered stimuli with different bandwidths including filtered from 0.5 to 5 kHz, 0.5 to 7 kHz, 0.5 to 11 kHz and 0.5 to 20 kHz to a group of 18 children, 10 young adults, and 14 older adults with measured thresholds to 12 kHz. Analysis was around age, hearing loss and pinna size; larger pinnas being found to modestly move prominent spectral notches to lower frequencies. Analysis found that there was no difference in localization in the azimuth (horizontal plane) of those older participants with hearing loss compared to the younger participants. However, in elevation (vertical plane) it was found that participants with larger pinnas and limited hearing loss could improve their localization ability with a broader noise. However, for older adults with a hearing loss from at least 30 to 40 dB HL and greater from 4 to 11 kHz, a broader stimulus could not compensate for the loss. This suggests that a hearing loss mainly limited to the EHF is likely to have an impact on localization ability in the vertical plane.

The other recent study by Dobreva, O'Neill, and Paige (2011) also used bands of noise with a category of 10 to 20 KHz. However, the focus of the study was mainly on central aging, and the authors attempted to account for the peripheral hearing loss of the older participants by increasing stimuli level in the frequency band between 10 and 20 kHz. Participants included young, middle aged and elderly with general age associated sensorineural hearing loss measured to 16 kHz. This set up included a two –axis robotic arm that covered +- 60 degrees horizontal and +- 25 degrees vertical, with 10 degree intervals and 13 locations. Stimuli was 150ms noise filtered from 0.1 to 20, 0.1 – 10, 0.1-1, 3-20 3-10 and 10-20 k Hz. The noise was presented at 70 -75 dB SPL with the exception of 80- 85 dB SPL in the band from 10-20 k Hz to take into account the high frequency hearing loss of the more elderly subjects. The study found that while horizontal precision of older participants and middle aged participants were significantly different than the younger groups in the 1250 to 1575 kHz bands, there was no overall significant effect in the horizontal plane.

In terms of vertical localization, Dobreva et al., (2011), found that by limiting the noise band to less than 10 kHz, errors were increased significantly. When the bandwidth was limited to frequencies between 10 and 20 kHz, this also occurred, possibly due to an absence of spectral notches in the 5 to 10 kHz range. Participants also localized with less precision and accuracy as they got older, which may be attributed to hearing loss and also a decline in the processing of spectral cues. These findings again suggest that a hearing loss in the EHF is likely to reduce localization ability in the vertical plane.

1.8 Goals of the Current Study

This main goal of this study is to determine whether any significant differences in localization ability can be found between participants, with (hearing loss group or without a hearing loss (normal hearing); mainly limited to the EHFs. This research was considered to be justified, because to the author’s knowledge, there is a gap in the literature that directly compares localization performance of participants with normal hearing (NH) versus those with a hearing loss (HL), using speech. In order to make comparisons between the groups a number of stimuli are to be used including speech with strong high frequency content above 8 kHz and speech with weak high frequency content above 8 kHz, both band-passed between 300 Hz and 8 kHz and 300 Hz and 16 kHz, and noise band-passed in a similar manner.

It is hypothesised that there is not likely to be significant differences in localization ability for the two groups in the horizontal plane due to low frequency information being available to all the participants. However, in the vertical plane it is hypothesized that the HL participants would localize less accurately than the NH participants due to the more limited high frequency information being available to them. This effect is also expected to be seen by the NH listeners when the high frequency content of the stimuli is removed due to the reduced spectral information (i.e. the stimuli is reduced to the 8 kHz band-passed condition from the 16 kHz band-passed condition).

A second aim of the research is to determine whether there is a difference in localization ability of noise stimuli and the two different speech stimuli. It is hypothesised in the vertical plane noise would be more accurately localized than high frequency strongly weighted speech followed by the weaker high frequency speech. This is due to the noise stimuli providing the most spectrally stable and easily localized information (Butler, 1986; Makous & Middlebrooks, 1990; Middlebrooks, 1992) in comparison to the speech. In the horizontal plane no significant difference between the stimuli is expected because of the strong low frequency information available in speech (Gilkey & Anderson, 1995).

Methods

Participants were recruited and tested via pure tone audiometry in order to assign them to either the normal hearing (NH) group or the hearing loss (HL) group. All participants then individually undertook localization tasks. The tasks involved best identifying which of 13 speakers were delivering broadband or filtered noise or speech stimuli. As will be described below, the speakers were spaced at 15° intervals on a hemispheric array that could be positioned horizontally or vertically. The participants could sit face on or side on to this array, allowing testing of localization in the frontal horizontal plane, lateral horizontal plane, frontal vertical plane, and lateral vertical plane. Responses were recorded for these four test positions and scored by degree of error (in 15° increments) using custom developed computer software. Statistical analyses were performed to compare localization ability between groups (normal hearing or EHF HL), between horizontal and vertical planes, and among different types of stimuli: broadband and filtered noise and broadband and filtered speech with strong and weak high frequency components. The study was approved by the University of Canterbury Ethics Committee. Subsections below provide detail of participant characteristics, instrumentation, procedures and statistics used in the study.

2.1 Participants

An initial pool of 69 volunteer participants were recruited from staff and students from the Departments of Communication Disorders, Chemistry and Physics at the University of Canterbury, along with residents in the surrounding region. Participants were recruited via word of mouth, internal University of Canterbury e-mail and information brochures left at the University of Canterbury Speech and Language Clinic (see Appendix 1 for the brochure and Appendix 2 for the participant consent form).

The hearing of each participant was tested via pure tone audiometry for the frequencies 0.25, 0.5, 1, 2, 4, 6, 8, 9, 10, 11.2, 12.5 and 14 kHz. Participants were divided into two groups depending on their hearing. If thresholds met certain criteria (described below), participants were asked if they would like to further participate in the localization tasks.

Participants were assigned to the NH group if their hearing thresholds did not exceed 20 dB HL at any of the frequencies 0.25,0.5,1,2,4,6,8,9,10,11.2,12.5 and 14 kHz; and between ear symmetry at each frequency was not greater than 15 dB. Criteria for inclusion in the EHF HL group were that participants had hearing thresholds not exceeding 20 dB HL up to and including 3 kHz, 30 dB HL or better at 4 kHz and a threshold of at least 55 dB HL in any of the frequencies from 8 kHz to 14 kHz and between ear symmetry no greater than 15 dB.

Twenty four participants did not meet the inclusion criteria; 13 (7 females and 5 males) due to their hearing thresholds not exceeding 55 dB HL at any of the frequencies of 8 to 14 kHz; 10 (4 females and 6 males) as their hearing thresholds were worse than 20 dB HL at one of the frequencies from 250 Hz to 4 kHz and 1 (a male) due to them having a greater than 15 dB difference in between ear hearing threshold symmetry. One further participant declined participating in the localization task due to a change in personal circumstances which made her unavailable. Participants in both groups reported they had no known middle ear dysfunction or auditory processing disorders.

2.1.1 Normal hearing group

There were 23 adult normal hearing participants aged between 18 and 39 years (mean age of 24.65 [±4.80] years). Sixteen were female and 7 were male. The mean pure tone thresholds for each ear for the normal hearing group are shown in Figure 9 below.

2.1.2 Hearing loss group

There were 23 adult participants, aged between 30 and 67 years (mean age of 53.7 ± 9.10 years) in the HL group. 16 were female and 7 were male. Figure 10 is a graphical representation of the average pure tone thresholds for the HL group of participants. At some frequencies there was no response by some participants. For the purposes of averaging and graphing, in those instances the highest level of the audiometer has been recorded as the threshold.

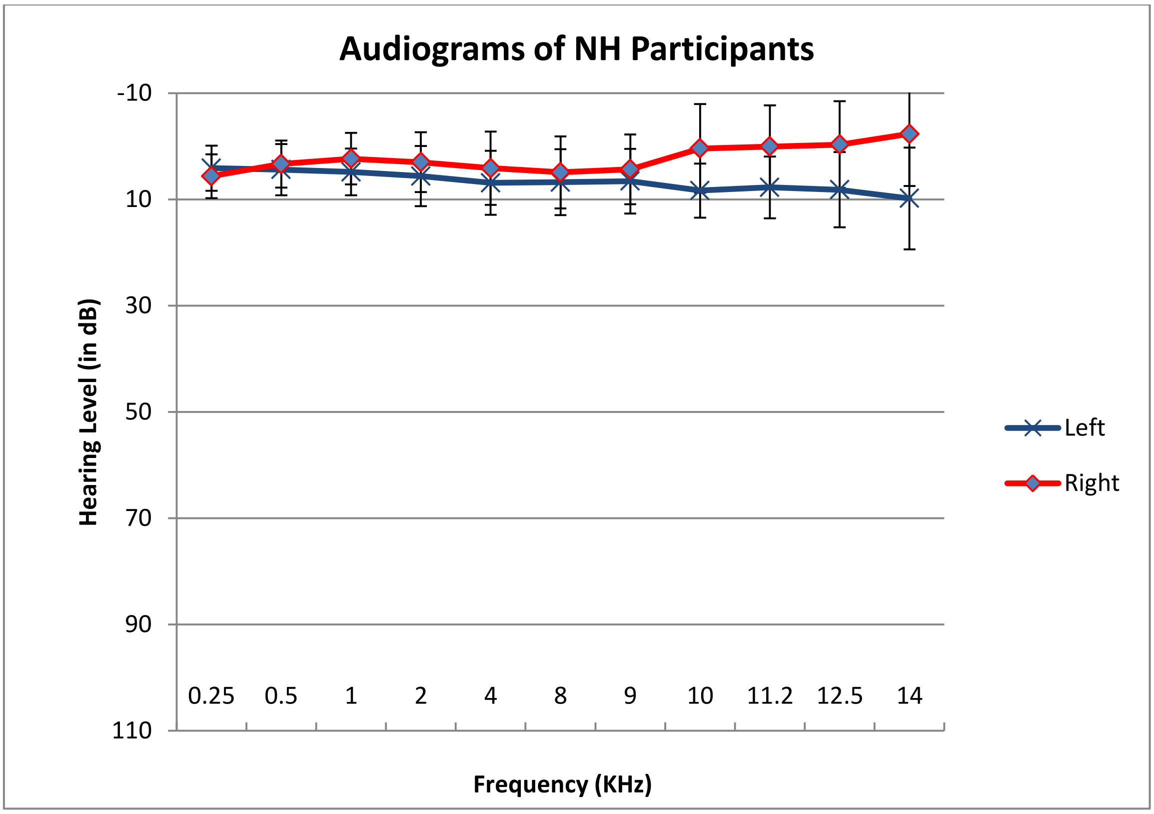


Figure 9. Average of hearing thresholds for the NH group. Error bars present standard deviation.

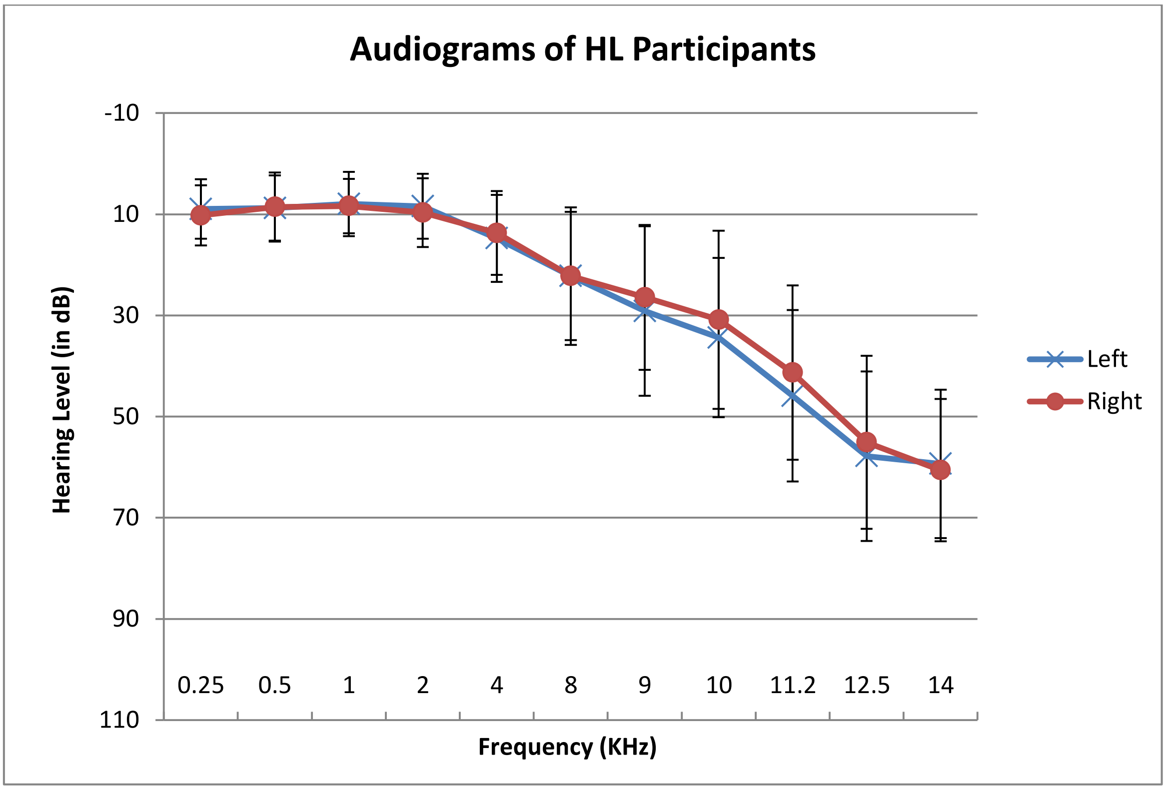


Figure 10. Average of hearing thresholds for the HL group. Error bars represent standard deviation.

2.2 Instrumentation

2.2.1 Testing room

The localization component of the experiment was conducted in a 2900(l) x 2730(w) x 2000(h) mm sound attenuating booth at the University of Canterbury. In order to reduce reverberation, the walls and ceiling were layered with sound absorbing foam 25 – 50 mm thick. In addition to this a layer of blankets and mats was laid on the floor. See Figure 11 for a view of the room layout.

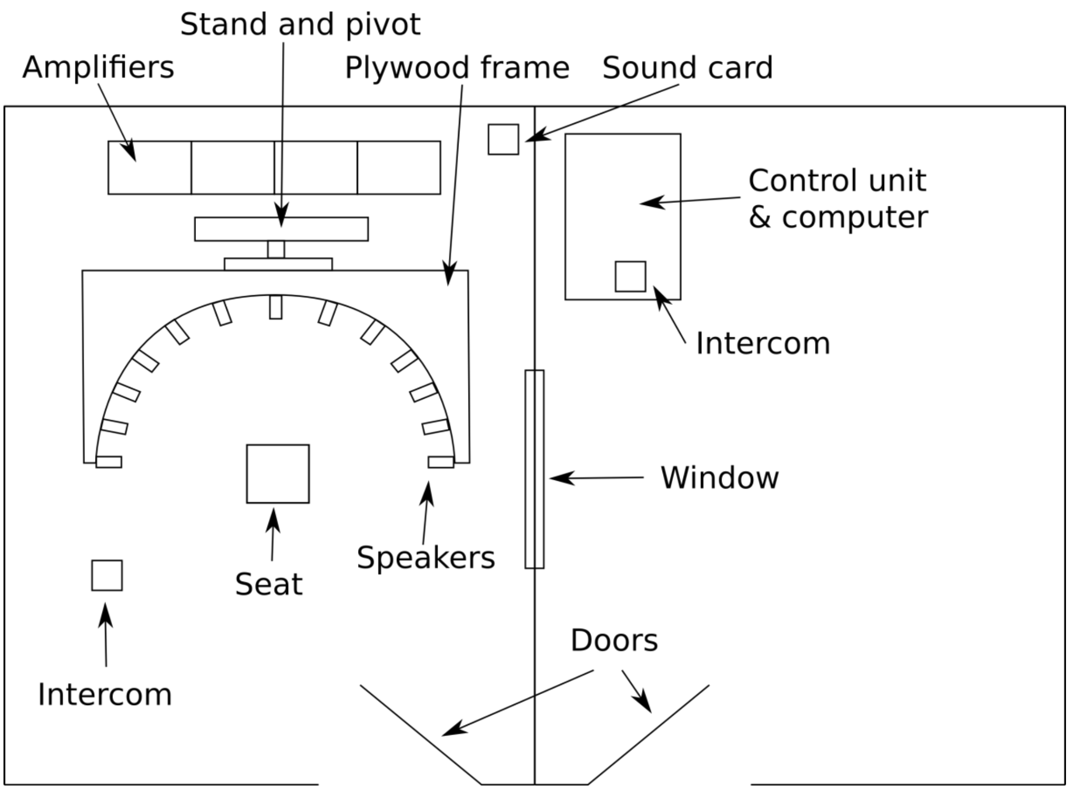


Figure 11. View of the room layout.

The hemispheric speaker array was positioned close to the back wall, speakers facing inwards with the participant sitting as closely to the middle of the room as possible. The sound card and amplifiers for the speakers were placed in a line along the floor between the speaker array and the wall. An internal 610 x 760 mm window connected the room to an adjacent room where the researcher sat with computer to present the stimuli. The researcher was positioned in the adjacent room so the participant and researcher could communicate visually, and the researcher could check the participant was sitting still and not turning toward the speakers prior to the end of the stimuli presentation. In addition to this there was one way verbal communication from the participant to the researcher via a wireless intercom. See Figure 12 for a schematic illustration of the hemispheric array.

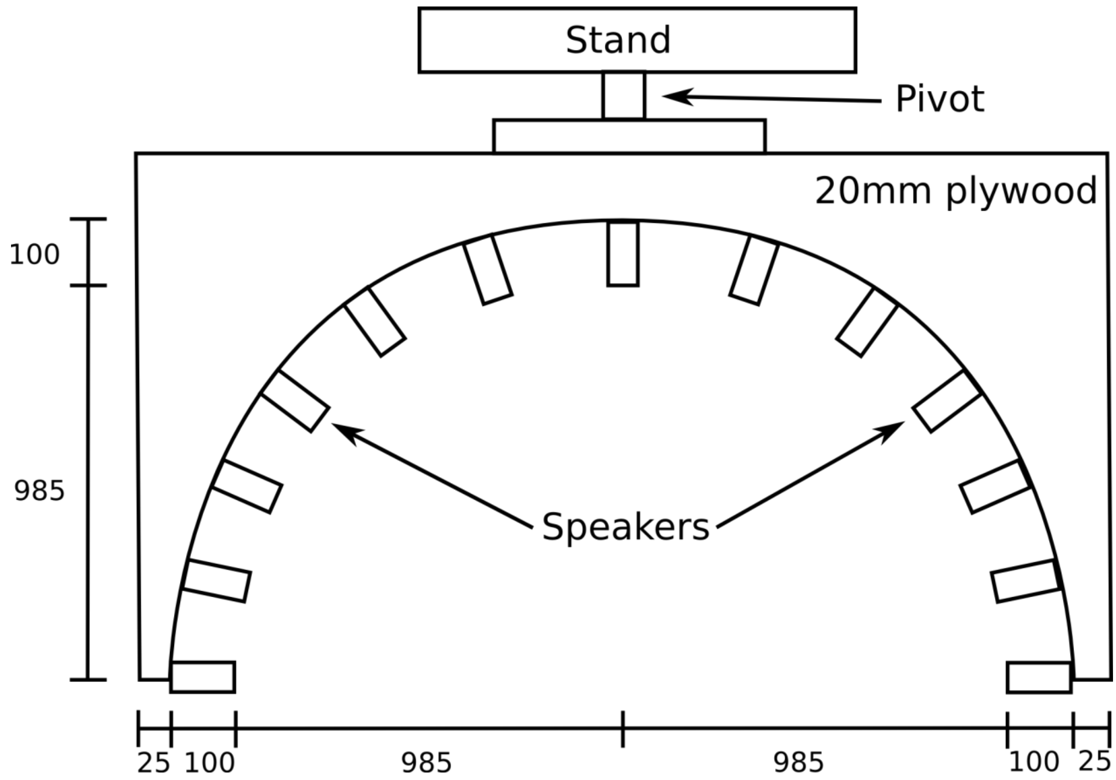


Figure 12. Design of the experimental equipment.

2.2.2 Experimental apparatus

The experimental apparatus was constructed using a 20 mm thick sheet of construction plywood that was sized to closely fit the height of the test room when in the vertical position. As the room had a height of approximately 2000 mm, so allowing for foam and a small margin for rotating the apparatus, the external width of the array was set at 1970 mm. From this an arc was cut, leaving a 25 mm thickness at the edges of the plywood sheet. The plywood sheet was attached via a mounting bracket to a modified engine hoist. The bracket was designed so that the pivot point on the hoist allowed the middle speaker to be in the centre of the room when the apparatus was in either the vertical or horizontal position.

The 13 speakers (dimension 125 by 75 mm) were attached using velcro strips to angle brackets that were screwed to the plywood sheet. The speakers were set 15 degrees apart as measured from the centre of the arc. The speakers were clearly numbered from 1 to 13, made from signs with numbers printed on white paper, and attached by velcro to the bottom of the speaker. When the apparatus was in the horizontal position, speaker number 1 was leftmost relative to the seated participant; when in the vertical position, speaker number 1 was at the lowest point. Once all speakers were attached, the radius from the cone of the leftmost or rightmost speaker to the centre of the arc was 985 mm.

2.2.3 Soundcard, amplifiers and speakers

The speakers and amplifiers were sourced from Inspire T6160 5.1 speaker systems manufactured by Creative Labs (Singapore). They were driven by a Motu mk3 multi-channel soundcard (Mark of the Unicorn, Cambridge, MA, USA). Sound was emitted from speakers 1, 3, 4, 6, 7, 9, 11 and 13. Speakers 2, 5, 8, and 12 were "virtual" speakers – they were physically present as icons for the participant, but the sound attributed to them was produced from a combined signal from the two adjacent speakers. There were four amplifiers, each driving two speakers (1+3, 4+6, 7+9, 11+13). Due to constraints of the number of outputs from the soundcard controlling the amplifiers, speaker 10 was a dummy speaker and while identical to the others did not emit any sound, either physically or virtually. The amplifiers each contained a sub-woofer, which was de-soldered to prevent it producing a low-frequency output during the experiments.

2.2.4 Localization software

In order to control the sound being presented from each speaker, Dr Greg O'Beirne developed a software package called the UC Directional Hearing Array. Screenshots are shown in Figure 13. The software had the ability to send a sound signal to any one of the functioning 12 speakers (8 physical, 4 virtual). There were six different types of sound stimuli which were each presented at four different presentation levels. The details of the types of stimuli and presentation level are discussed in section 2.2.5 and 2.2.6.

For each participant, the software program sequentially ran through the sound presentations for each of the stimuli conditions before prompting the researcher to alter the plane of orientation of the speakers as required for each of the two plane conditions. In order to minimise any practise effect or issues of fatigue, the noise and speech stimuli were run in the following sequence: noise followed by speech for the first participant and then speech followed by noise for the second participant. In addition, the first participant of each testing day started the localization tasks with the orientation of the speakers being in the horizontal position followed by the vertical position. The second participant then started the localization tasks with the speaker orientation being in the vertical position first. This also helped to minimise any order effects and reduced the moving of the equipment by the researcher.

The information recorded by the software program for each participant included:

1. Experiment number and plane
2. Time from commencement of experiment
3. Stimulus type (HF Strong/HF weak)
4. 8-16 kHz Energy
5. Filter band (300-8000 Hz/300-16000 Hz)
6. Presentation level (73, 74.33. 75.67 and 77 dB A)
7. Virtual channel (1=yes/0=no)
8. Presentation angle (0 to 180 degrees or -90 to 90 degrees depending upon plane)
9. Selected angle (0 to 180 degrees or -90 to 90 degrees depending upon plane)
10. Error of selection (degrees)

This information was summarised visually on the screen and a result log and corresponding confusion matrix was produced and saved for each participant. The result log also contained summary information of the means for the various conditions. The software was run on a Hewlett Packard Compaq nx6120 laptop.

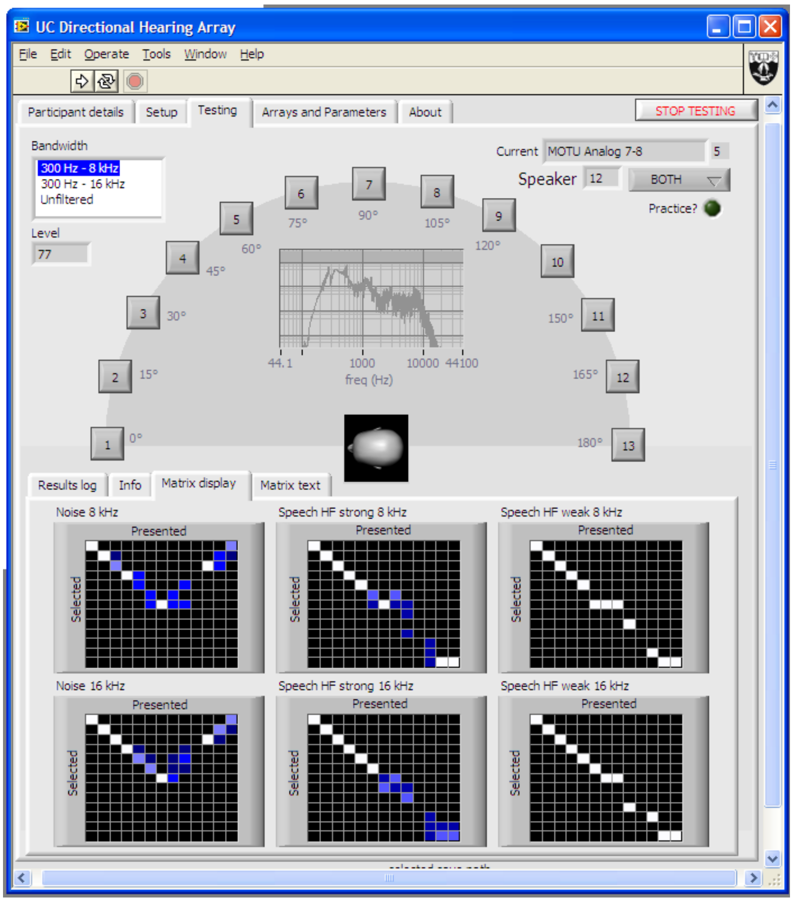


Figure 13. Screenshot of the localization software showing the array of speakers and matrix display of the six different stimuli.

A separate programme was also developed by Dr Greg O'Beirne to speed up the analysis of the data. This programme summarised individual participants' error for each experiment and stimuli.

2.2.5 Level

The stimuli were presented at four levels of 73.00, 74.33, 75.67 and 77 dB A to give an average level of 75 dB A. This roving of sound level was to counteract the effect of the participant moving their body slightly or not being exactly in the centre of the speaker array.

2.2.6 Stimuli

The type of stimuli included:

1. Broadband noise band-pass filtered between 300 Hz and 16 kHz
2. Broadband noise band-pass filtered between 300 Hz and 8 kHz.
3. Speech stimuli of single words band-pass filtered between 300 Hz and 16 kHz:
    a. Words with strong high frequency content.
    b. Words with weak high frequency content.
4. Speech stimuli of single words band-passed between 300 Hz and 8 kHz:
    a. Words with strong high frequency content.
    b. Words with weak high frequency content.

For stimuli type 1 and 2, the duration of the noise was 150 ms with a short rise-decay cosine of 10 ms as longer rise-decay cosines can provide onset cues (Yost, Loiselle, Dorman, Burns, & Brown, 2013).

The words used for stimuli 3 and 4 were from the Harvard word list (Egan, 1947) and were taken from ten lists of 100 phonetically balanced words spoken by a female actor. These words were generously supplied by Assoc. Prof. Simon Carlile (Department of Physiology, the University of Sydney) and had been recorded using a Brüel and Kjær 2610 amplifier (Brüel and Kjær, Nærum, Denmark) and digitized at a sample rate of 80 kHz using an anti-aliasing filter with a 30 kHz cut off. These words were specifically recorded to provide high frequency content which is often filtered out when recording with lower bandwidths, and to minimise background noise which could provide unwanted cues and effect localization performance. See Best et al., (2005) for further information about the recording technique.

As shown in Figure 14, the words from the ten lists were ranked from top to bottom with respect to frequency content between 8 kHz and 16 kHz. One hundred and forty four words were chosen from words that had high frequency content above 8 kHz and the top 33% of those words were used for the strong speech condition. Forty eight words were taken from the bottom 15% of the list and were used for the weak speech condition. These words with EHF content were selected in order to maximise the likelihood that any effect of the high-frequency content on localization performance would be measured as a significant difference. A list of the words can be found in Appendix 3.

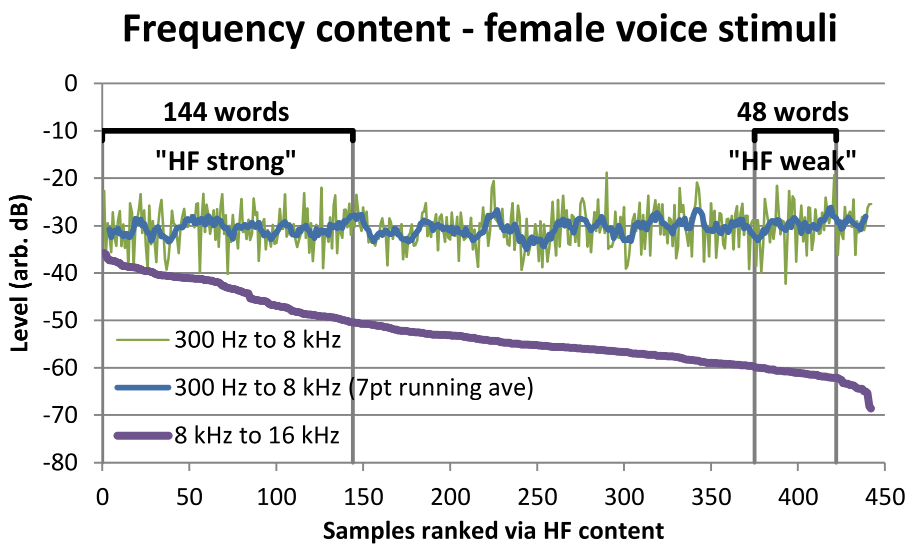


Figure 14. The speech stimuli were ranked according to their frequency content between 8 kHz and 16 kHz. A set of 144 consecutive words from the top 33% formed the “HF strong” group, and 48 consecutive words from the bottom 15% formed the “HF weak” group. There was no significant difference in the frequency content of the two groups between 300 Hz and 8 kHz.

Each participant received the following stimuli in each of the array orientations:

NOISE CONDITION - PRACTICE:

4 stimuli, presented in random order, consisting of the following:

- *Bandwidths:* 2 stimuli filtered from 300 Hz – 8 kHz, and 2 from 300 Hz – 16 kHz. *Levels:* 1 stimulus presented at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* Each of the 4 presentations from a different one of the 12 channels (8 physical, 4 virtual) selected randomly.

NOISE CONDITION - TEST:

96 stimuli, presented in random order, consisting of the following:

- 48 noise burst stimuli. *Bandwidths:* 300 Hz to 8 kHz. *Levels:* 12 stimuli at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* 4 presentations from each of the 12 channels (8 physical, 4 virtual) at each of the four available levels.
- 48 noise burst stimuli. *Bandwidth:* 300 Hz to 16 kHz. *Levels:* 12 stimuli at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* 4 presentations from each of the 12 channels (8 physical, 4 virtual) at each of the four available levels.

SPEECH CONDITION - PRACTICE:

- 4 "HF strong" speech stimuli*. Bandwidths:* 2 at 300 Hz to 8 kHz, and 2 at 300 Hz to 16 kHz. *Levels:* 1 stimulus presented at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* Each of the 4 presentations from a different one of the 12 channels (8 physical, 4 virtual) selected randomly.

SPEECH CONDITION - TEST:

96 stimuli, presented in random order, consisting of the following:

- 36 "HF strong" speech stimuli. *Bandwidth:* 300 Hz to 8 kHz. *Levels:* 9 stimuli at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* 3 presentations from each of the 12 channels (8 physical, 4 virtual) at three of the four available levels.
- 36 "HF strong" speech stimuli. *Bandwidth:* 300 Hz to 16 kHz. *Levels:* 9 stimuli at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* 3 presentations from each of the 12 channels (8 physical, 4 virtual) at three of the four available levels.
- 12 "HF weak" speech stimuli. *Bandwidth:* 300 Hz to 8 kHz. *Levels:* 3 stimuli at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* 1 presentation from each of the 12 channels (8 physical, 4 virtual) at one of the four available levels.
- 12 "HF weak" speech stimuli. *Bandwidth:* 300 Hz to 16 kHz. *Levels:* 3 stimuli at each of the four levels (73, 74.33, 75.67, and 77 dB). *Channels:* 1 presentation from each of the 12 channels (8 physical, 4 virtual) at one of the four available levels.

2.2.7 Calibration

To ensure that the sound levels from each presentation speaker for all experiments was constant, the equipment was calibrated prior to experimentation. During calibration, sound output and frequency was measured via a Brüel & Kjær 4942 ½" diffuse field microphone positioned in the centre of the speaker array and connected to a 94 dB PULSE system and laptop running LABSHOP. Calibration of the microphone took place with a 94 dB 1kHz Brüel & Kjær 4231 calibrator.

Broadband noise was presented through the speaker array. An A-weighted Fast Fourier Transform (FFT) of the SPL was measured at the centre of the array. FFT specifications included a bandwidth of 200 kHz, df of 125Hz and averaging time of 4 seconds. The frequency response of the amplifier and speaker combination was thereafter "corrected for" in the software through the application of an inverse FFT filter to every stimulus prior to delivery in order to create a flatter resulting frequency response, particularly in the high frequencies. The measured frequency response of the amplifiers and speakers before (grey) and after this correction (black) can be seen in Figure 15.

A similar inverse filter process was used to ensure that both the noise and the speech stimuli were produced at the same output level when the bandwidth was 300 Hz to 16 kHz. When a bandwidth of 300 Hz to 8 kHz was used, the level correction was applied prior to filtering out the 8 kHz to 16 kHz frequency region.

The sound level for each of the speaker channels (both physical and virtual) was set at 75 dB A by placing a sound level meter in the centre of the array (in the position of the participant's ear), and playing a long continuous noise sequentially (bandwidth: 300 Hz to 16 kHz) through each channel (i.e. through speaker 1, then speakers 1 and 3 simultaneously for the virtual speaker 2, then speaker 3, and so on). The sound level meter reading was recorded from outside the booth and entered into the software. The output level through that particular channel was then adjusted during the experiment to produce an output level of 75 dB A (e.g. if the sound level meter reading was 78.7 dB A for speaker 1, the output for that speaker was reduced by 3.7 dB during the experiment to achieve a level of 75 dB A). This was checked by repeating this calibration procedure with the corrections in place. The process was repeated whenever the output levels of the amplifiers or soundcard were altered in any way.

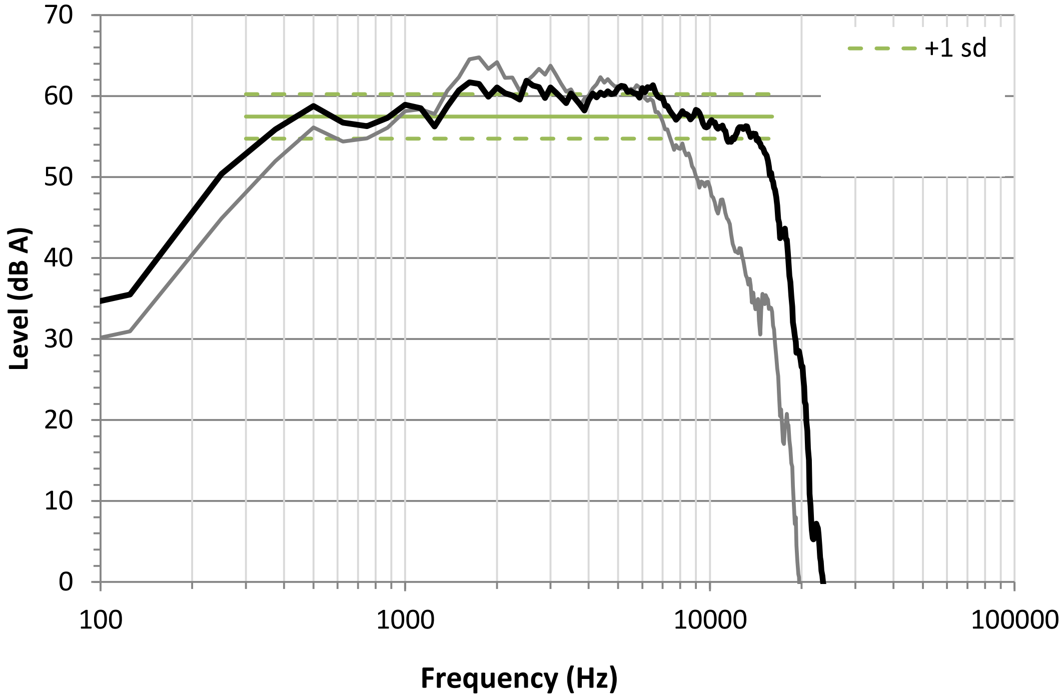


Figure 15. The measured frequency response of the Creative Inspire T6160 5.1 amplifier and speaker systems before correction (grey) and after correction (black) using an inverse FFT filter process.

2.3 Procedure

2.3.1 Pure-tone audiometry

Diagnostic pure tone audiometry was conducted to screen the potential participants into one of three groups; normal hearing, extended high frequency hearing loss, and unsuitable. The testing took place in a sound treated booth at the University of Canterbury, Department of Communication Disorders Audiology Clinic using a GSI clinical audiometer. Telephonics TDH supra-aural headphones were the transducers used for the frequencies 250 to 8000 Hz and Sennheiser HDA 200 headphones for frequencies from 9000 Hz to 14000 Hz. Thresholds of 16 kHz were not included due to issues of test-retest variability

(Schmuziger et al., 2004). The modified Hughson-Westlake procedure determined the air conduction audiometric thresholds for 0.25, 0.5, 1, 2, 4, 8, 9, 10, 11.2, 12.5, 14 kHz and for each subject in each ear (Cahart, 1959). This technique follows the standard procedure taught at the University of Canterbury.

Additional bone conduction was performed at 4 kHz on 3 participants whose air conduction threshold was greater than 20 dB HL at 4 kHz. This was to check that their hearing loss was sensorineural in nature, by confirming that their bone and air conduction thresholds for that frequency were within 10 dB HL.

2.3.2 Localization testing

Participants were seated in the middle of the semi-circular arrangement of speakers facing frontwards or sideways. The four measurement positions or experiments can be seen in figures 16 to 19, and include facing front on to the speakers in the frontal horizontal plane (Experiment 1 – frontal horizontal plane), side on to the speakers in the horizontal plane (Experiment 2 – lateral horizontal plane), front on to the speakers when the arc is turned to the vertical plane (Experiment 3 – frontal vertical plane) and side on to the speakers in the vertical position (Experiment 4 - lateral vertical plane). For each experiment the participants were seated with their ear at the level of the centre of the speakers. This was done using a measuring stick and a chair with an adjustable height.

Prior to each experiment, the participant was asked to focus straight in front of them. They were then instructed to listen for the speech or noise and at the end of the presentation turn and call out the number of the speaker they had identified. Instructions provided to the participant prior to the experiment commencing can be found in Appendix 4. The number of the speaker called out was transmitted via the intercom and recorded electronically by the researcher in the software program by the researcher. The next presentation of stimuli was triggered by the entering of the previous data.

Prior to each experiment, four practise stimuli were presented to familiarise the participant with the task and speaker locations. Noise stimuli were presented if the noise condition was first, or speech stimuli if the speech condition was first. After completion of the first condition, the practise stimuli for the second condition were presented. No feedback was provided during testing. A break was provided halfway through the testing (i.e. after completion of either both horizontal or both vertical orientations) at which time the array was moved into a different plane by the researcher.

Figure 16. Experiment 1 position – frontal horizontal plane.

Figure 17. Experiment 2 position – lateral horizontal plane.


Figure 18. Experiment 3 - frontal vertical plane (left); and

Figure 19. Experiment 4 – lateral vertical plane (right).

2.4 Testing Assumptions

2.4.1 Recorder reliability

To check the reliability of recording by the researcher of the speaker number the participant perceived the stimuli to come from, another researcher also recorded the speaker numbers for three participants on a piece of paper. This was done independently, with the researcher and second recorder having no interaction.

2.4.2 Left and right ear assumption

As the participants' hearing was essentially symmetrical between ears, the assumption was made in the case of Experiment 2 and 4 (where the participant was sitting side on to the speakers) that there would be no difference in localization ability regardless of whether the right or left ear was nearer the speaker. This assumption was tested for Experiment 2 and 4 by recording localization ability for five of the participants in the study using both their right and left ears.

2.5 Statistical Analysis

Data for the participants were collated in a Microsoft Excel spread-sheet and comparisons were calculated in The Statistical Package for the Social Sciences (SPSS). Further description of the analysis follows.

2.5.1 Statistical analysis within Experiments 1 to 4

Error matrices

The error matrices were produced from the output logs of the software package UC Hearing Array to allow a visual display and comparison of the performance of individual participant's localization performance across all stimuli conditions. Each error matrix contains the information drawn from all the repetitions for an individual participant for a particular stimuli condition, for example noise 8 kHz.

The presentation speaker location is on the x-axis. For Experiment 1 and Experiment 3 in the frontal plane, the speakers are numbered from -90° on the left to 90° on the right. For Experiment 2 and Experiment 4 in the lateral plane, the speakers are numbered from 0° on the left to 180° on the right. Note that there is no result at 135° as this was the dummy speaker.

The participants selected speaker location is on the y-axis. For Experiment 1 and Experiment 3 in the frontal plane, the selected speakers are numbered from -90° at the top to 90° on the bottom. For Experiment 2 and Experiment 4 in the lateral plane, the speakers are numbered from 0° on the top to 180° on the bottom.

As there were different amount of repetitions for the different stimuli types, the matrices contain different amounts of data points. (For noise there were 48 repetitions, and for speech strong and speech weak there were 36 and 12 repetitions respectively).

2.5.1.2 Analysis of large errors of selection

In order to obtain a greater understanding of the kind and extent of errors participants were making and better compare them with other literature, the percentage of large errors were calculated. These were defined the same as in Best et al. (2005), as individual results that had an error of greater than 90° between presentation and selection angles. For each participant, the number of large errors for each stimuli were calculated and divided by the number of presentations for each stimuli (48 presentations for noise, 36 for strong speech and 12 for weak speech) in order to obtain the percentage for each participant.

These errors were not required for Experiment 1 (frontal horizontal plane) as there were not any large errors of selection for either HL or NH participants due to the accurate localization of all participants. It was also decided not to examine Experiment 3 for large errors as there did not appear to be any up/down errors and there were several participants who appeared to not have any correlation between angles of presentation and selection of the stimuli.

ANOVA model

A four-way (2 hearing status x 3 signal types x 2 frequency filter types x 13 locations) Mixed Model Analysis of Variance (ANOVA) was conducted on each of the four experiments on the mean errors of selection for each of the experimental conditions with hearing status (hearing loss vs. normal hearing groups) as the between-subjects factor and arrangement, signal type (noise, weak speech, and strong speech), frequency (8 kHz vs. 16 kHz), and location as the within-subjects factors. Significance level was set at 0.05.

Post hoc tests using the Bonferroni correction were conducted for each significant ANOVA interaction. The significant interactions are reported in the results. In addition, the pairwise comparison graphs drawn based on the output data produced by SPSS have been placed in Appendix 5. The graphs are included as they visually display the information from the post hoc tables that could otherwise be difficult to interpret.

Across experiment statistical analysis

A five-way (2 hearing status X 4 arrangements X 3 signal types X 2 frequencies X 13 locations) Mixed Model Analysis of Variance (ANOVA) was conducted on the measure of the extent of error, with hearing status (hearing impaired vs. normal hearing groups) as the between-subjects factor and arrangement, signal type (noise, weak speech, and strong speech), frequency (8 kHz vs. 16 kHz), and location as the within-subjects factors. Significance level was set at 0.05. As for the within experiment analysis, post hoc comparisons can be viewed in graph form in Appendix 5.

Results

3.1 Experiment 1. Frontal Horizontal Plane

Figures 20 and 21 display the confusion matrices for the individual participants for all stimuli (noise, strong speech, weak speech) and frequency filter conditions (8 kHz and 16 kHz) in the frontal horizontal plane. The angle of presentation is on the x-axis and angle of selection is on the y-axis. For this experiment, the angles range from -90 degrees (left most speaker) to 90 degrees (right most speaker). As discussed earlier in Section 2.5, if there was 100% correct selection by the participants the points on the graph would follow a perfect -1 gradient with no deviations. It can be seen from the graphs that in general there is good fit for the majority of the results, with some increased variation for the more peripheral speakers (-90° to -75° and 75° to 90°), for example HL participants 14 and 15 and NH participants 25 and 34. Visual examination of the error matrices did not indicate any obvious overall difference between the hearing loss group (HL) and the normal hearing group (NH).

The mean participant selection error and standard deviation for five representative location points across Experiment 1 are presented in Table 1. Five location points were included in order to demonstrate the trends in means and standard deviations across the experiment, as variation was found at different speaker locations, meaning an overall mean and standard deviation was not considered particularly informative. The lowest mean error of selection was 0.0°± 0.00 for the central speaker location (0°) for several stimuli conditions, (for example speech strong 8 kHz) for both the HL and NH groups. This indicated accurate localization. The highest mean error of selection for the HL group was for noise 8 kHz at speaker location 90° (14.8° ± 7.4), whereas for the NH group the highest mean error of selection was 12.6° ± 5.6 for noise 8 kHz at speaker location -90°. A graphical illustration of the mean error of selection and the standard deviations is shown in Figures 22 and 23.

A four-way ANOVA was conducted in order to determine whether there was any significant difference between the HL and NH groups with respect to mean error of selection, and whether this was impacted on by the different stimuli (noise, strong speech and weak speech), frequency filter conditions (8 kHz and 16 kHz), and speaker location (-90° to 90°). Further investigations of the interactions were conducted with a series of independent t-tests conducted with Bonferroni adjustments at the 95% level (i.e. $p < .05$). The ANOVA table can be seen in Table 2 and the post hoc graphs found in Appendix 5.

Overall, there was no significant main effect for the two groups for mean error of selection, $F(1, 44) = 284.56$, $p = .99$. However, as explained below, there was a significant main effect for signal type, $F(2, 44) = 64.21$, $p < .001$, frequency, $F(1, 44) = 14.688$, $p < .001$) and speaker location, $F(12, 528) = 91.62$, $p < .001$. Further investigation revealed significant interactions between signal and location, $F(24, 528) = 8.37$, $p < .001$, frequency and location $F(24, 1056) = 5.37$, $p < .001$, and hearing, signal and frequency $F(2, 88) = 5.57$, $p = .005$.

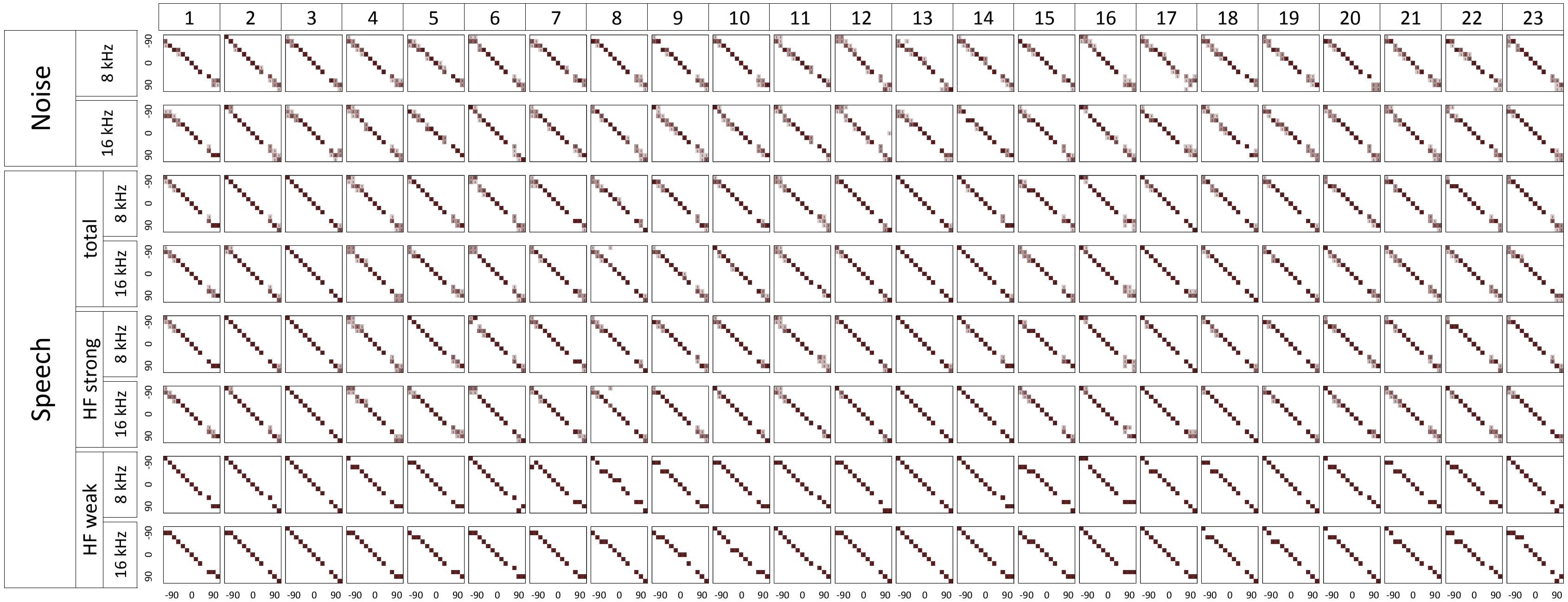


Figure 20. Confusion matrices for hearing loss participants (HL) for Experiment 1. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

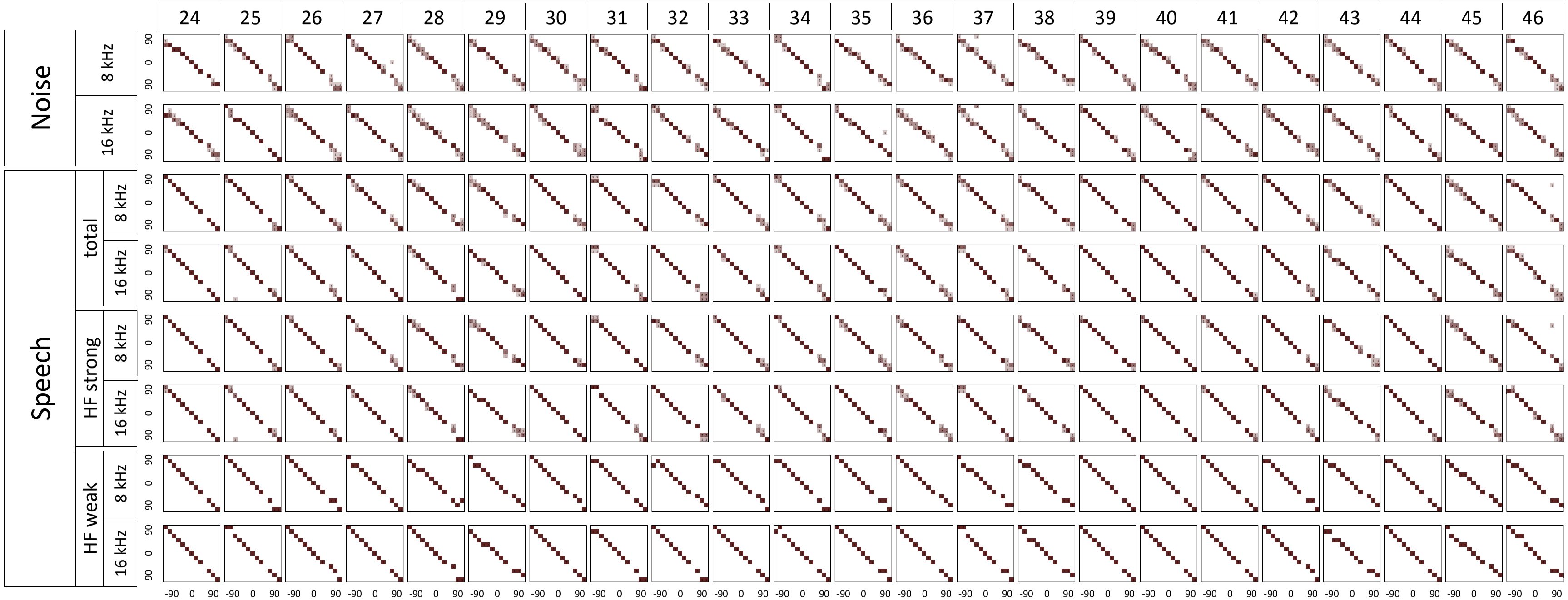


Figure 21. Confusion matrices for normal hearing participants (NH) for Experiment 1. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

It was found that for the noise condition there was a significantly lower mean error of selection for the 16 kHz filter frequency compared to the 8 kHz filter frequency for the HL group ($p < 0.05$). For example, mean error rate at speaker location 60° for HL participants was 9.9° ± 4.3 for 8 kHz compared to 7.3° ± 4.9 for 16 kHz. Likewise, there was a significantly lower mean error of selection in the NH group for the speech weak condition with 16 kHz having a better localization result compared to 8 kHz. At the same speaker location of 60°, mean error rate was 3.9° ± 6.7 for 8 kHz compared to 2.6° ± 5.8 for 16 kHz.

Noise was also found to have a higher mean error rate of selection than the other stimuli types, consistent with improved localization performance for speech compared to noise. This can be seen in Table 1 when comparing means, for example mean error rate for HL speaker location -90° for noise 8 kHz was 12.4° ± 5.0 compared to 7.8° ± 10.0 for speech weak 8 kHz. Likewise, for NH the mean was 3.1 ± 5.1 for 16 kHz total speech at 90° speaker location compared to 10.3 ° ± 7.0 for 16 kHz noise at the same location.

When examining the effect of speaker location (regardless of stimulus type), it can be clearly seen in Table 1 and Figures 22 and 23 that the mean error and standard deviation of selection for the speakers at the front of the participants (-45°, -30°, -15°, 0°, 15° and 30°) were lower than the more peripheral speakers (-90°, -75°, 75°, 90°). For example, for speaker location 0° (i.e. straight in front of the participant) the mean error rate ranged from 0.0° ± 0.0 for 8 and 16 kHz filtered speech for the HL participants, and 16 kHz filtered noise, 8 kHz filtered strong and weak speech for the NH participants to a maximum of 0.7° ± 3.1 for weak 8 kHz filtered speech for the HL participants. In comparison the mean errors of selection and standard deviation were much greater at the peripheral speakers. For example, at speaker location -90°, the mean ranged from 2.6° ± 5.8 for the weak 16 kHz filtered speech for the NH participants to 12.6° ± 5.6 for the 8 kHz filtered noise, also for the NH participants. This showed that there was less accuracy and a greater variability of localization performance at the more peripheral speakers.

When comparing frequency and location, the speakers toward the periphery (-90°, 90°) had significantly higher mean errors of selection for 8 kHz compared to 16 kHz ($p < 0.05$). There were significant differences for mean error of selection between noise and both speech types at speaker locations -90°, -75°, -60°, -45°, -30°, 60°, 75° and 90° ($p < 0.05$). At speaker locations -75° and 75°, speech strong was localized significantly better than speech weak ($p < 0.05$).

Table 1. Mean error of Selection (±SD) for five speaker locations for Experiment 1. HL group (Table a) and NH group (Table b).

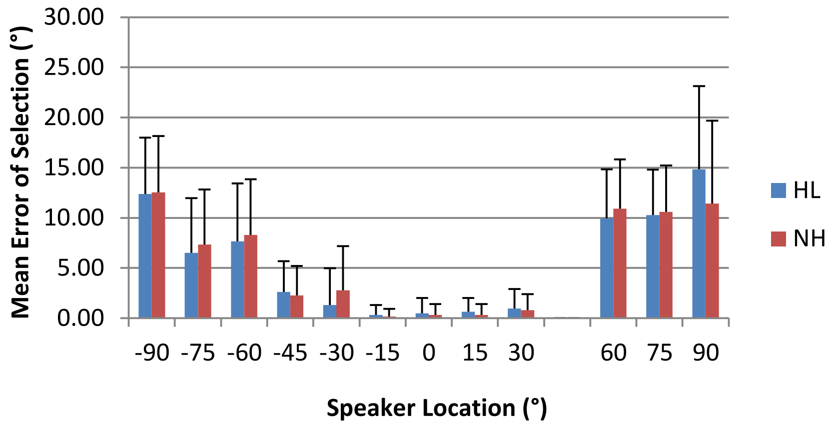
a. Hearing loss participants

		Speaker -90°		Speaker -60°		Speaker 0°		Speaker 60°		Speaker 90°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	12.4	5.0	7.7	5.4	0.5	1.7	9.9	4.3	14.8	7.4
	16 kHz	8.2	7.2	7.5	4.7	0.2	0.8	7.3	4.9	10.8	6.4
Speech											
Total	8 kHz	6.8	5.5	3.6	4.3	0.2	0.8	3.9	3.8	8.5	5.6
	16 kHz	4.9	4.0	2.1	2.7	0.0	0.0	2.8	4.0	8.0	6.2
Strong	8 kHz	6.5	5.3	3.5	4.4	0.0	0.0	3.9	4.3	8.0	5.4
	16 kHz	3.9	4.0	1.7	2.4	0.0	0.0	2.8	4.2	7.4	6.7
Weak	8 kHz	7.8	10.0	3.9	6.7	0.7	3.1	3.9	6.7	9.8	8.6
	16 kHz	7.8	7.7	3.3	6.3	0.0	0.0	2.6	5.8	9.8	8.6

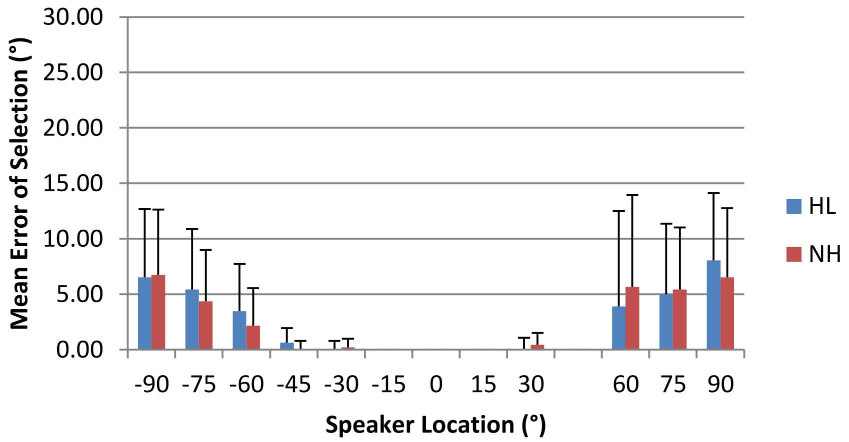
b. Normal hearing participants

		Speaker -90°		Speaker -60°		Speaker 0°		Speaker 60°		Speaker 90°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	12.6	5.6	8.3	5.5	0.3	1.1	10.9	4.9	11.4	8.3
	16 kHz	9.5	6.8	8.0	5.3	0.0	0.0	10.1	5.1	10.3	7.0
Speech											
Total	8 kHz	7.0	5.9	2.1	3.4	0.0	0.0	5.5	8.3	6.5	6.2
	16 kHz	3.4	4.9	4.6	9.0	0.2	0.8	4.1	4.5	3.1	5.1
Strong	8 kHz	6.7	6.3	2.2	3.6	0.0	0.0	5.7	10.7	6.5	6.1
	16 kHz	3.7	5.9	5.2	11.2	0.2	1.0	4.6	5.4	3.0	5.2
Weak	8 kHz	7.8	8.9	2.0	5.2	0.0	0.0	5.2	7.3	6.5	8.8
	16 kHz	2.6	5.8	2.6	5.8	0.0	0.0	2.6	5.8	3.3	6.3

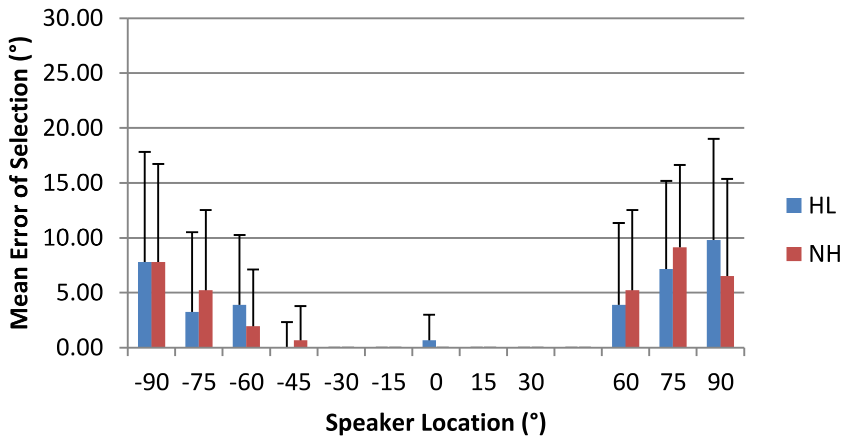
Note. Mean is the mean error of selection in degrees.



a. Noise

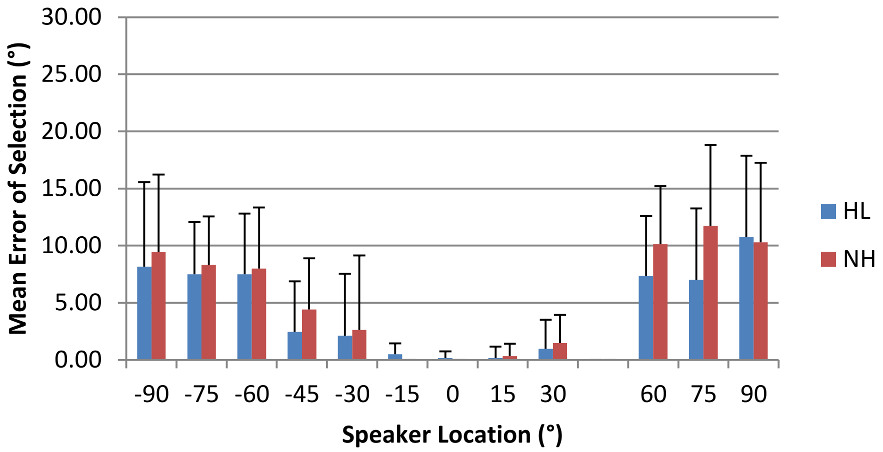


b. Strong speech

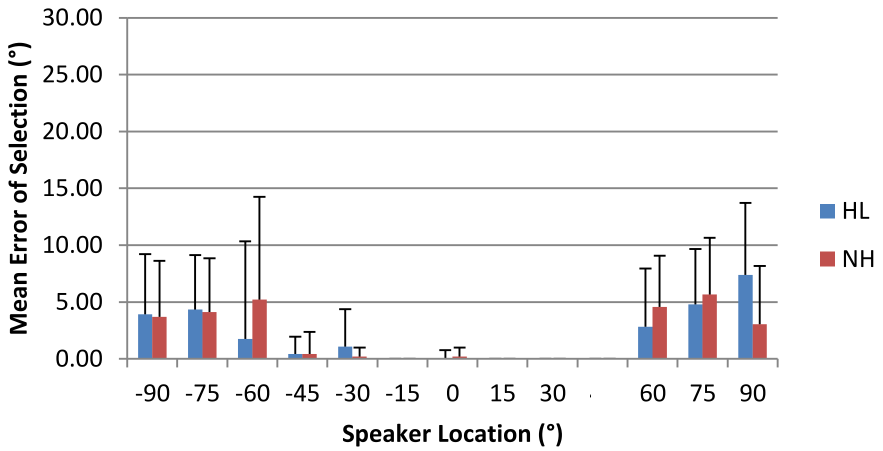


c. Weak speech

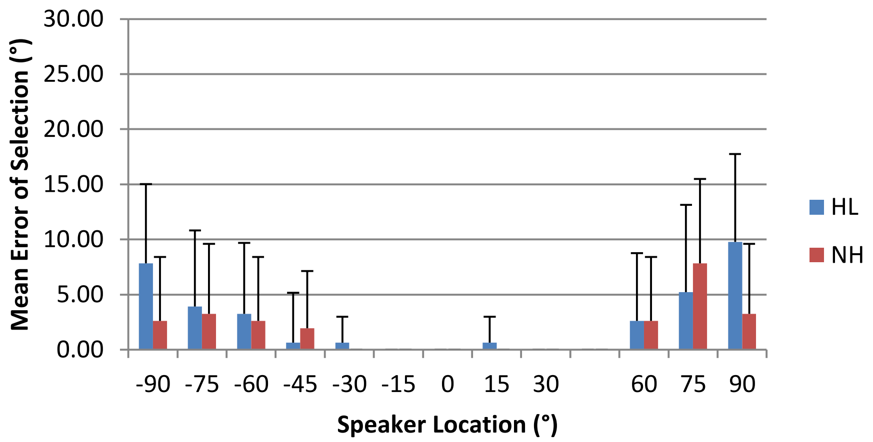
Figure 22. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (a. noise, b. strong speech, and c. weak speech) in Experiment 1, for the 8-kHz filtered frequency condition.



a. Noise



b. Strong speech



c. Weak speech

Figure 23. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (a. noise, b. strong speech and c. weak speech) in Experiment 1, for the 16-kHz filtered frequency condition.

Table 2. Summary of the four-way analysis of variance for Experiment 1.

Source	Hypothesis df	Error df	F	P
Hearing (H)	1	44	284.557	0.99
Signal (S)	**2**	**44**	**64.207**	**<0.001***
Frequency (F)	**1**	**44**	**14.688**	**<0.001***
Location (L)	**12**	**528**	**91.614**	**<0.001***
H x S	2	88	1.375	0.254
H x F	1	44	0.165	0.687
H x L	12	528	2.912	0.018
S x F	2	88	0.205	0.814
S x L	**24**	**528**	**8.37**	**<0.001***
F x L	**24**	**1056**	**5.372**	**<0.001***
H x S x F	**2**	**88**	**5.57**	**0.005***
H x S x L	24	1056	0.824	0.585
H x F x L	12	528	1.236	0.29
S x F x L	24	1056	0.486	0.892
H x S x F x L	24	1056	1.316	0.222

Note. Significance level is 95%. Data showing a significant difference is marked with a bold font and asterix.

3.2 Experiment 2. Lateral Horizontal Plane

Figures 24 and 25 display the confusion matrices for the individual participants for all stimuli and frequency conditions. As with Experiment 1, the angle of presentation is shown on the x-axis and angle of selection is shown on the y-axis. For this experiment the angles of presentation range from speaker location 0°, directly in front of the participant to speaker location 180°, directly behind the participant. Speaker location 90° is parallel to the right ear of the participant. For explanation regarding interpretation of the error matrices refer to Section 2.5.1.1. Visual assessment of the graphs demonstrates there is generally better localization ability in the speaker range 0° to 90 °, which is directly in front to the right side of the participants (i.e. the front right quadrant), compared to locations from 90 ° to 180 °, which is opposite the right ear of the participant to directly behind the participant (i.e. the right rear quadrant) This is evidenced by the relatively straight line of the data in the presentation range for speaker location 0° to 90°, but a far wider range of selection results in the presentation range for speaker location 90° to 180°. It can be seen that some participants, for example HL participant 3 for Noise 8 kHz and HL participant 20 for all stimuli conditions demonstrate front/back confusions. The types of error will be discussed later in Section 3.6.

The four way ANOVA (see Table 4) confirmed there was no significant main effect of mean selection error between the two hearing groups $F(1, 43) = 0.012$, $p = .913$, or any significant main effect attributable to filter frequency type (8 kHz and 16 kHz) $F(1, 43) = 2.055$, $p = 0.159$. However, as described below, there was a significant main effect for signal type (noise, speech strong and speech weak) $F(2, 86) = 23.19$, $p < .001$, and presentation location of the stimuli $F(12, 516) = 20.306$, $p < .001$. There were also significant interactions for signal by location, $F(24, 1032) = 4.45$, $p = 0.005$, signal by frequency by location, $F(24, 1032) = 2.124$, $p = 0.05$, and hearing by signal by frequency by location $F(24, 1032) = 2.436$, $p = 0.025$. A series of post hoc pairwise comparisons using the Bonferroni adjustment were conducted at the 95% level. Examination of the pairwise comparisons could not find the significant comparison that resulted in a significant interaction involving hearing type. This is probably due to the large amount of variation and relatively low means at speaker locations 0° and 15°. The comparisons for the significant interactions can be found in Appendix 5.

The descriptive statistics for Experiment 2 can be seen in Table 3 and Figures 26 and 27. No obvious differences in localizing ability can be seen for either group across any of the experimental conditions.

No significant effect was found between the 8 kHz and 16 kHz frequency conditions $F(1,43) = 2.055$, $p = .159$). The 16 kHz conditions were generally localized similarly to the 8 kHz conditions for both hearing groups. For example, at speaker location 90°, the mean error of selection was 8.0° ± 5.7 for 8 kHz noise and 6.5° ± 4.6 for 16 kHz for the HL group. For the NH group, at speaker location 150°, the mean error of selection was 34.6° ± 40.4 for 8 kHz noise and 30.8° ± 42.0 for 16 kHz noise.

In terms of signal type, speech was found to be localized significantly better than noise $F(2, 86) = 23.19$, $p < .001$. This significant difference between noise and both speech types was only found for speaker locations 60° and 120° ($p < .05$). For example the mean error of selection was 1.1° ± 3.1 for 16 kHz speech total, compared to the noise mean error of selection of 2.4° ± 4.2 (speaker location 30°) for the NH group. While there were large differences at speaker locations 150° to 180°, due to the large individual variability, these were not found to be significant ($p > .05$). There was not a significant difference between the signal types speech strong and speech weak ($p > .05$).

The smaller means and standard deviations for speaker locations at the front of the participants (speaker locations 0°, 30°, 45) reflects better localization performance toward the front compared to behind (speaker locations 150°, 165°, 180°). An example for the HL participants were means ranging from 0.0° ± 0.0 kHz (8 kHz and 16 kHz strong speech) for speaker location 0° compared to 39.3° ± 64.3 and 37.6° ± 53.2 (8 kHz and 16 kHz strong speech respectively) at speaker location 180°. This difference in mean error of selection due to speaker location was significant ($p < .05$).

The NH participants localized in a similar manner to the HL participants with more accurate localization occurring in the front (0° speaker location), with means ranging from 0.0° ± 0.0 (16 kHz noise and 16 kHz speech) to 2.6° ± 12.5 (8 kHz strong speech). In comparison, directly behind the person mean error of selection ranged from 30.9° ± 58.1 (for 16 kHz speech) to 63.3° ± 78.7 (for 16 kHz noise). This difference in mean error of selection due to location was significant ($p < .05$).

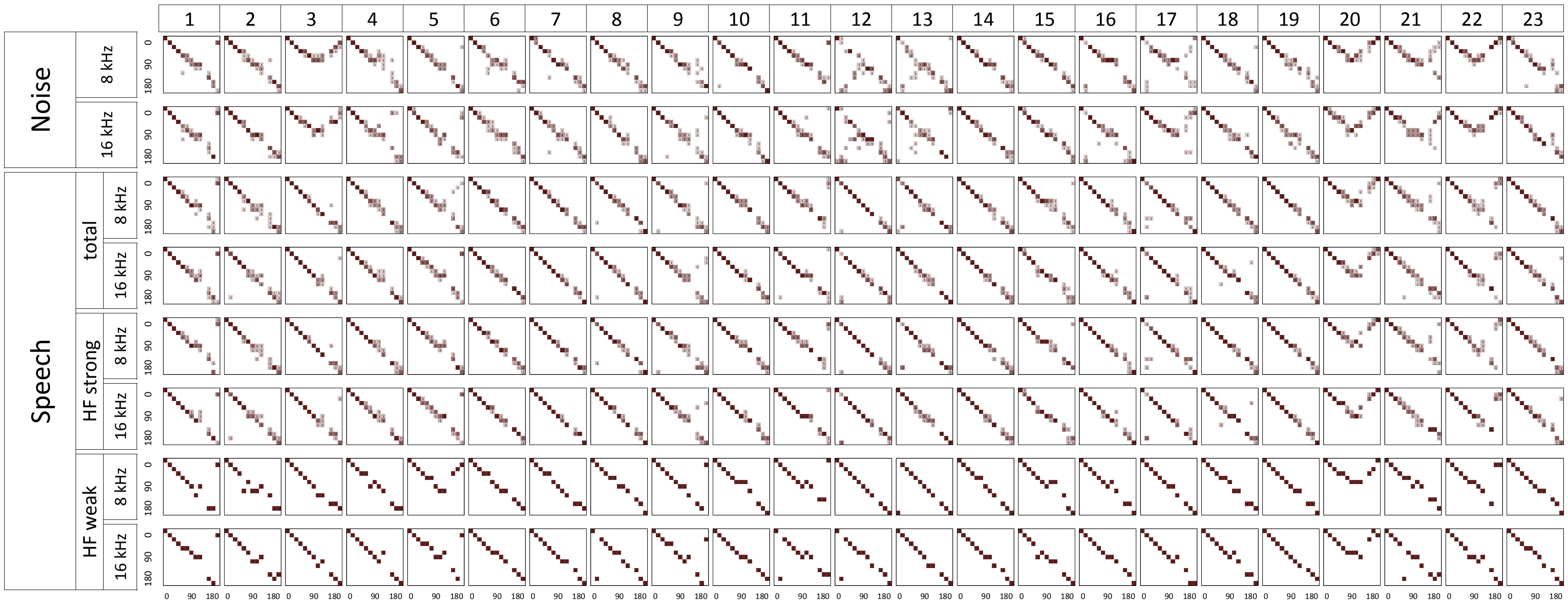


Figure 24. Confusion matrices for HL participants for Experiment 2. The angle of presentation is on the **x-**axis and angle of selection is on the y-axis.

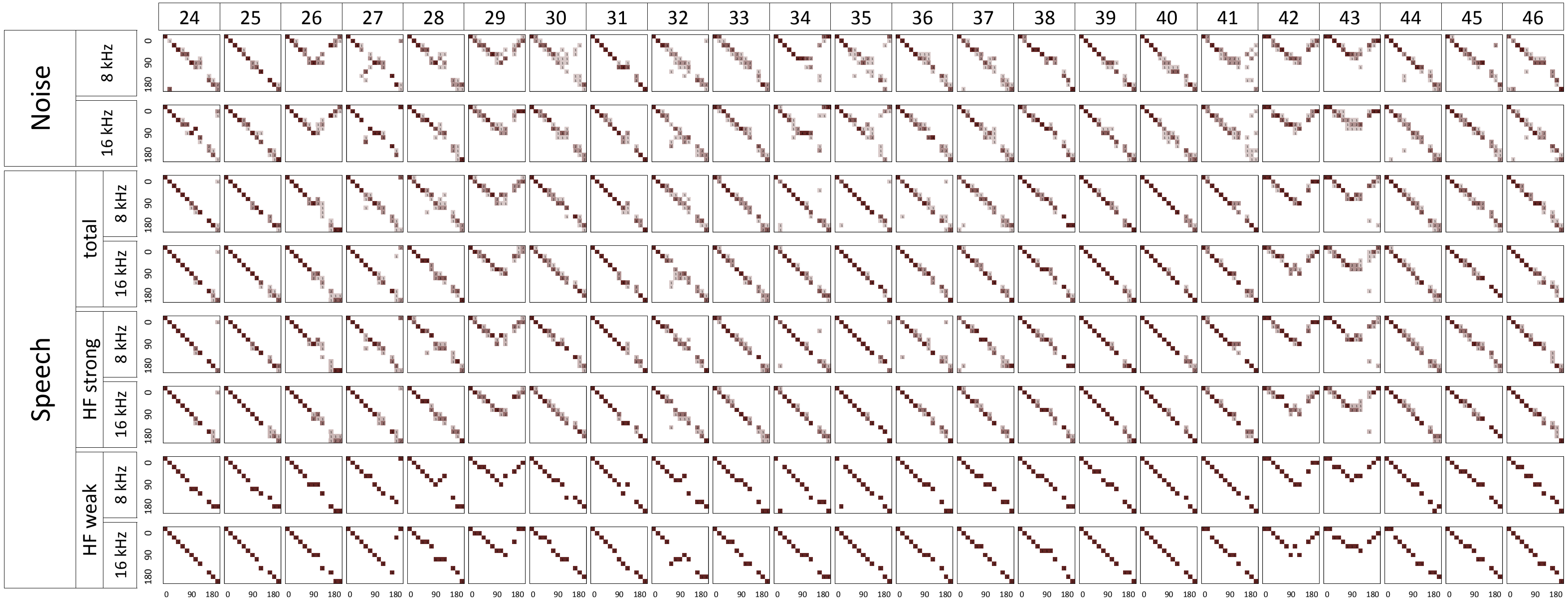


Figure 25. Confusion matrices for NH participants for Experiment 2. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

Table 3. Mean error of selection (±SD) for five speaker locations for Experiment 2. HL group (Table a) and NH group (Table b).

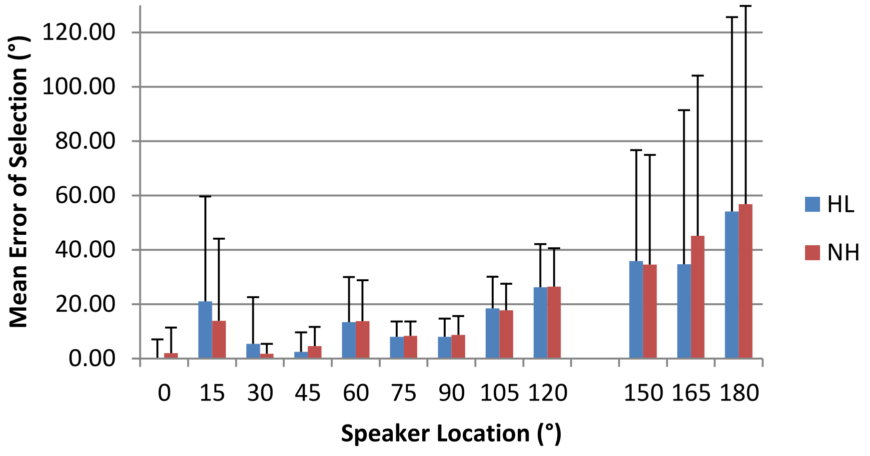
a. Hearing loss participants

		Speaker 0°		Speaker 30°		Speaker 90°		Speaker 150°		Speaker 180°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	0.0	0.0	5.4	22.6	8.0	5.7	35.9	36.7	54.1	61.6
	16 kHz	3.9	13.0	3.4	14.0	6.5	4.6	37.0	38.1	69.9	72.9
Speech											
Total	8 kHz	2.0	9.4	1.1	5.5	4.2	3.6	17.9	25.0	41.7	63.1
	16 kHz	0.0	0.0	0.0	0.0	2.8	3.0	14.7	24.6	36.7	51.1
Strong	8 kHz	0.0	0.0	1.5	7.3	4.3	4.3	18.7	25.9	39.3	64.3
	16 kHz	0.0	0.0	0.0	0.0	2.2	3.3	14.8	25.4	37.6	53.2
Weak	8 kHz	7.8	37.5	0.0	0.0	3.9	6.7	15.7	29.8	48.9	73.9
	16 kHz	0.0	0.0	0.0	0.0	4.6	7.1	14.3	24.1	33.9	60.7

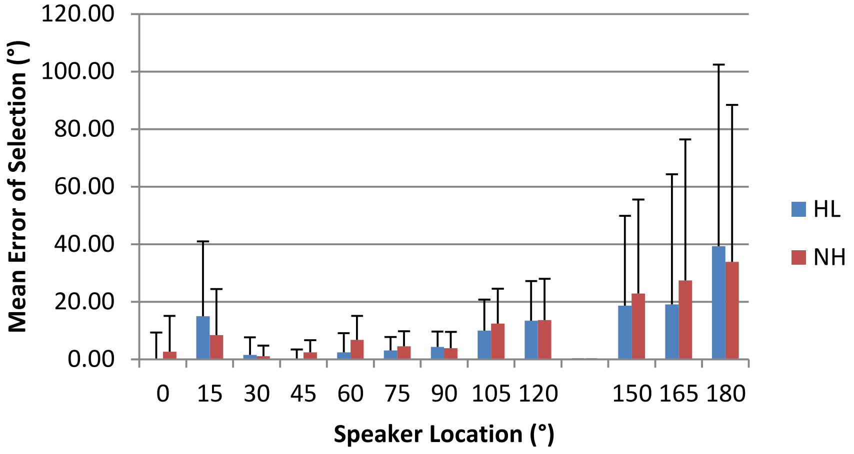
b. Normal hearing participants

		Speaker 0°		Speaker 30°		Speaker 90°		Speaker 150°		Speaker 180°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	2.0	9.4	1.8	3.6	8.6	7.0	34.6	40.4	56.7	73.0
	16 kHz	0.0	0.0	2.4	4.2	9.1	9.2	30.8	42.0	63.3	78.7
Speech											
Total	8 kHz	2.0	9.4	1.0	3.2	4.6	5.3	22.5	33.0	34.2	56.3
	16 kHz	0.0	0.0	1.1	3.1	5.2	6.0	20.9	34.0	31.5	58.8
Strong	8 kHz	2.6	12.5	1.1	3.7	3.9	5.6	22.8	32.7	33.9	54.5
	16 kHz	0.0	0.0	1.1	3.0	5.2	5.7	21.7	33.9	30.9	58.1
Weak	8 kHz	0.0	0.0	0.7	3.1	6.5	7.6	21.5	35.8	35.2	64.9
	16 kHz	0.0	0.0	1.3	4.3	5.2	8.6	18.3	35.0	33.3	65.7

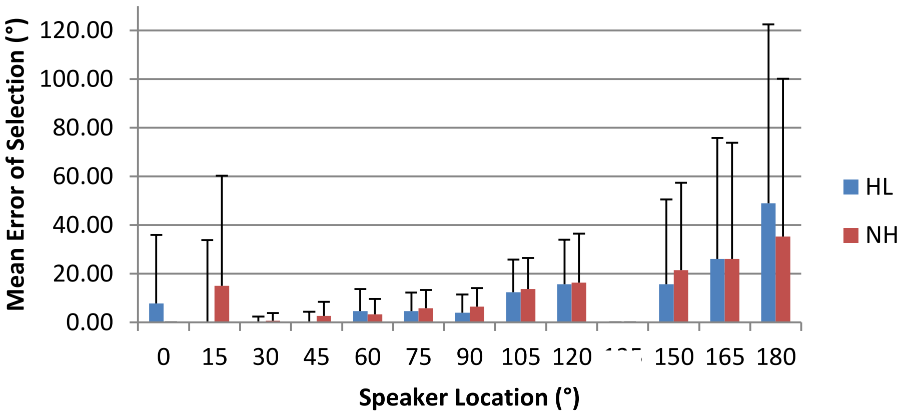
Note. Mean is the mean error of selection in degrees.



a. Noise

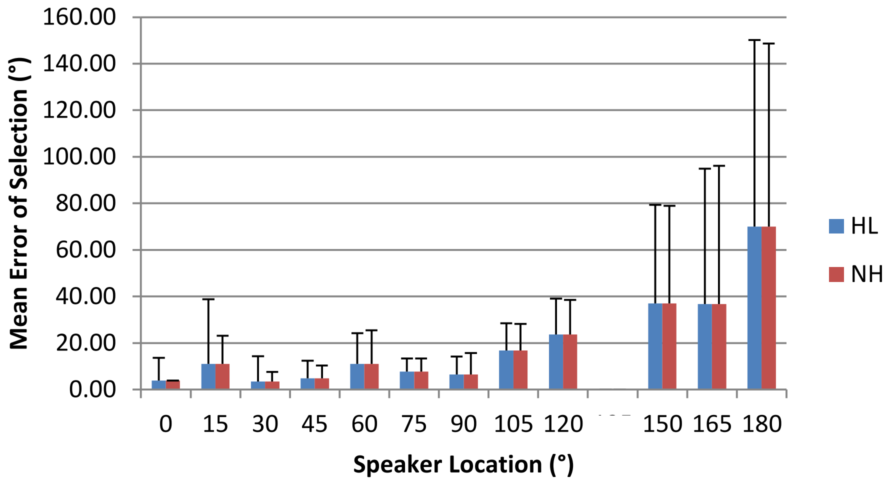


b. Strong speech

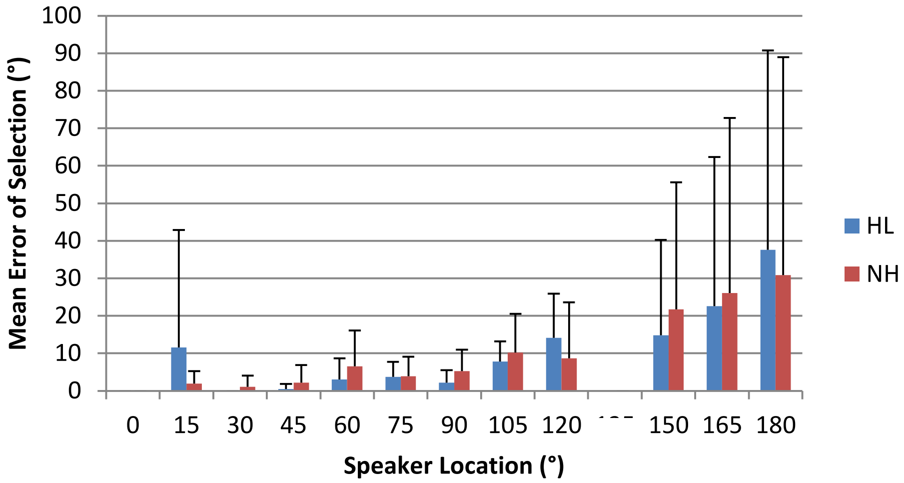


c. Weak speech

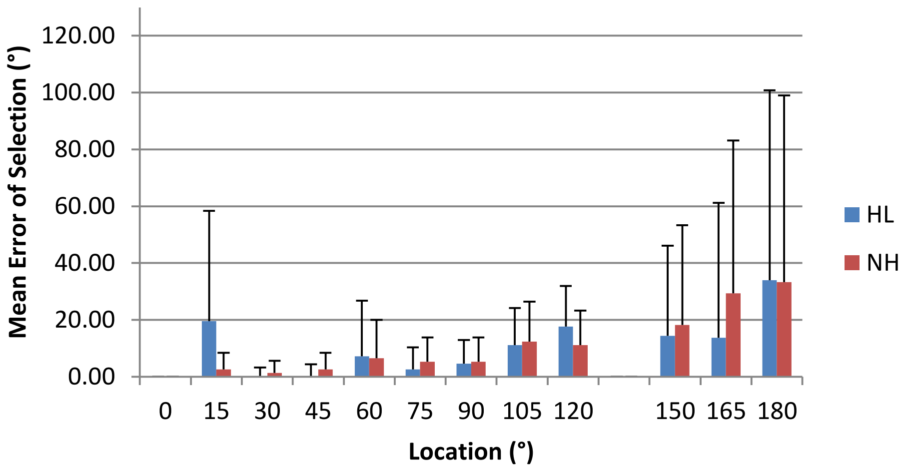
Figure 26. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (noise, weak speech, and strong speech) in Experiment 2, with signals in the 8-kHz filter condition.



a. Noise



b. Strong speech



c. Weak speech

Figure 27. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (noise, weak speech, and strong speech) in Experiment 2, with signals for the 16-kHz filter condition.

Table 4. Summary of the four-way analysis of variance for Experiment 2.

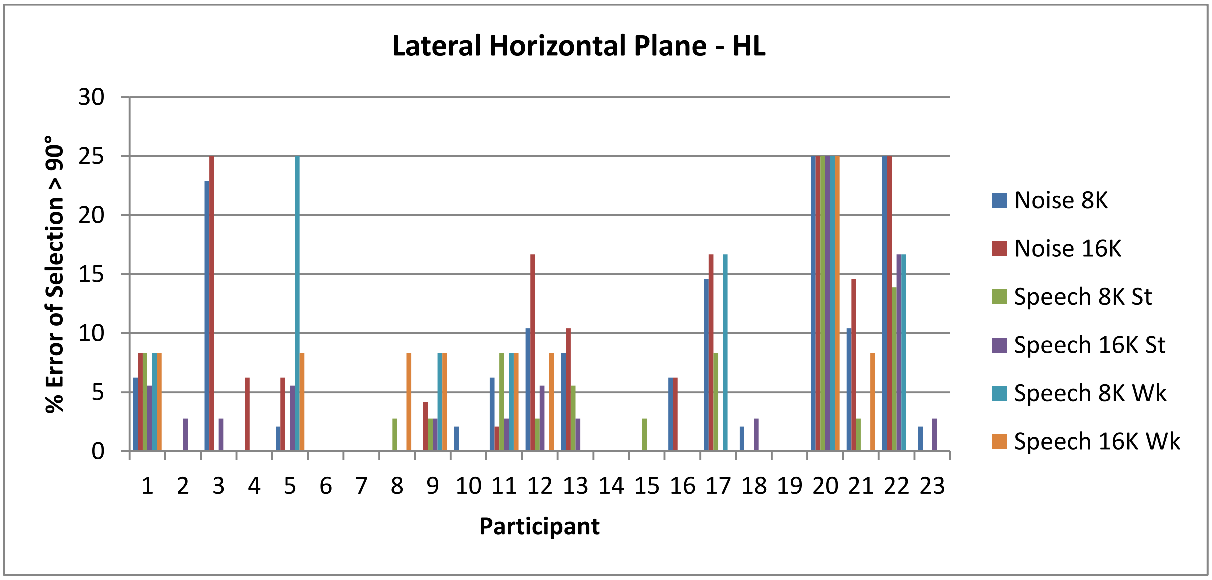
Source	Hypothesis df	Error df	F	P
Hearing (H)	1	43	0.012	0.913
Signal (S)	**2**	**86**	**23.18**	**<0.001***
Frequency (F)	1	43	2.055	0.159
Location (L)	**12**	**516**	**20.306**	**<0.001***
H x S	1	86	0.019	0.925
H x F	1	43	0.079	0.78
H x L	12	516	0.345	0.653
S x F	2	86	1.101	0.327
S x L	**24**	**1032**	**4.45**	**0.005***
F x L	12	516	0.435	0.749
H x S x F	2	86	0.33	0.943
H x S x L	24	1032	0.437	0.734
H x F x L	12	516	0.851	0.478
S x F x L	**24**	**1032**	**2.124**	**0.05***
H x S x F x L	**24**	**1032**	**2.436**	**0.025***

Note. Significance level is 95%. Data showing a significant difference is marked with a bold font and asterix.

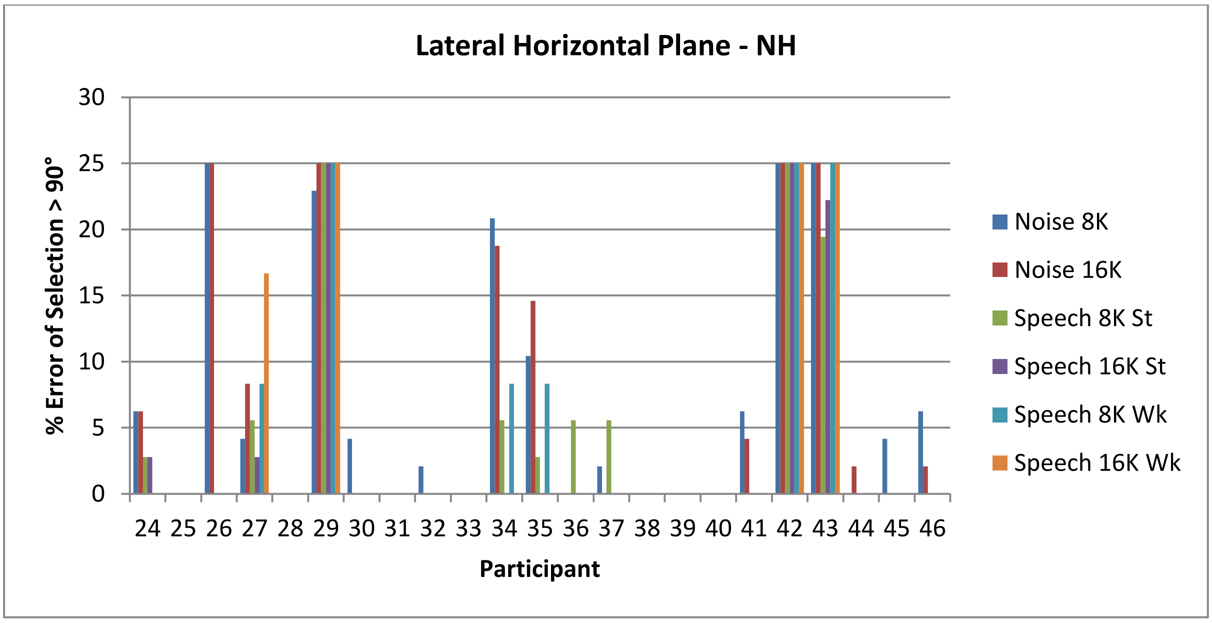
3.2.1 Examination of the large errors of selection

The large standard deviations seen in Table 3 for Experiment 2, especially as the speaker location increases from 150° to 180° is due in part to the poor localization performance of several individual participants. For example, it can be observed in Figure 22 and 23 that HL participant 20 and NH participants 29, 42 and 43 all have a large number of their percentage selection errors greater than 90°. Other studies, e.g. Best et al., (2005), have classified selection errors greater than 90° as “high selection angle errors”. From Figure 24 and 25 it can be seen that these four participants display typical front/back errors in their selection of speakers for all sound and frequency conditions. Other participants e.g. HL 3 and NH 26, and to a lesser degrees NH 34 and 35 display the front/back errors only for both noise conditions indicating that the noise condition has the most participants displaying a front/back type error. There are no other apparent trends of high selection error for the other sound and frequency conditions.

However, overall these large selection errors are made by only a small percentage of the participants, with only a total of six participants from both groups having a mean error of selection defined as high (>90°) for more than one condition (e.g. HL participant 20 and NH participants 29, 42). It was therefore decided not to remove the participants with high mean selection errors from the statistical analysis. Figure 28 provides a graphical illustration of these high errors of selection for the individual participants all the experimental conditions in Experiment 2.



(a) Hearing loss participants



(b) Normal hearing participants

Figure 28. Percentage of selection errors made by individual participants that were greater than 90°. (a) HL Participants, (b) NH Participants.

3.3 Experiment 3. Frontal Vertical Plane

Figures 29 and 30 display the confusion matrices for the individual participants for all stimuli and frequency conditions tested in Experiment 3. For this experiment the angles range from -90° (directly below the participant) to 90° (directly above the participant) in the frontal vertical plane. It can be seen from Figures 29 and 30 there is a large amount of variability in the confusion matrices for both groups. This can be seen from the means and standard deviations (see Table 5) and in Figures 31 and 32. Some individual participants e.g. HL 34 and NH 2, do not appear to follow any clear localization trend.

Examination of the four-way ANOVA for Experiment 3 (see Table 6) confirms that there was no significant main effect of hearing type on mean error of selection for the participants $F(1, 44) = 2.972$, $p = 0.092$. However, there were significant main effects for signal type $F(2, 88) = 13.095$, $p < 0.001$), frequency filter type, $F(1,44) = 14.591$, $p < .001$) and location, $F(12, 528)$, $p = < .001$). There was also a significant interaction between frequency and location $F(12, 528) = 6.364$, $p < .001$ and hearing type by frequency filter type by location, $F(12, 528) = 1.953$, $p < 0.5$.

Post hoc pairwise comparisons confirm that in Experiment 3, noise signal type (23.8° ± 1.744) has a significantly higher mean error of selection compared to both speech strong (18.2° ± 1.191) and speech weak (19.8° ± 1.242) ($p < .05$). Overall, the two types of speech are not significantly different from each other in terms of mean error of selection ($p > .05$). This demonstrates that in the frontal vertical plane the participants from both groups localized better using speech sounds compared to noise. Refer to Appendix 5 for post hoc graphs.

There was a significant three way interaction between hearing, frequency, and speaker location ($F(12, 528) = 1.953$, $p = .027$), which indicates there are a number of complex patterns in the results. Overall, the results show that the HL participants localize more poorly than NH participants for speaker locations that are directly below them (i.e. -90°, -75° and -60°) for all speech and both frequency conditions ($p < .05$), compared to the speaker locations which are in front or above (-45° to 90°). For example, the mean error of selection for noise 8 kHz was 41.7° ± 56.2 (for speaker location -90°) compared to directly in front (25.6° ± 14.7 for speaker location 0°) and directly above (27.7° ± 15.7 for speaker location 90°). However, for the higher elevations (60°, 75° and 90°) it is the HL group who localize better than NH group for both frequency conditions. However this difference between the HL and NH mean errors of selection is only significant at speaker location 75° for both frequency conditions ($p < .05$).

For both strong and weak speech stimuli there is greater localization accuracy for the speakers in front of the participants (i.e. speaker locations -30°, -15°, 0° and 15°). However, this improvement was not significant ($p > .05$). However, localization performance for these speaker locations (-30°, -15°, 0° and 15°) is significantly improved by the 16 kHz filter condition for both the HL and NH participants compared to the 8 kHz filter condition ($p < .05$). An example of this from Table 5 can be seen for the HL group noise condition, where in the 8 kHz filter condition there is a mean error of selection of 25.6° ± 14.7, compared to the 16 kHz noise condition where there is a mean of 10.9° ± 11. Refer to appendix 5 for further details on the pairwise comparisons.

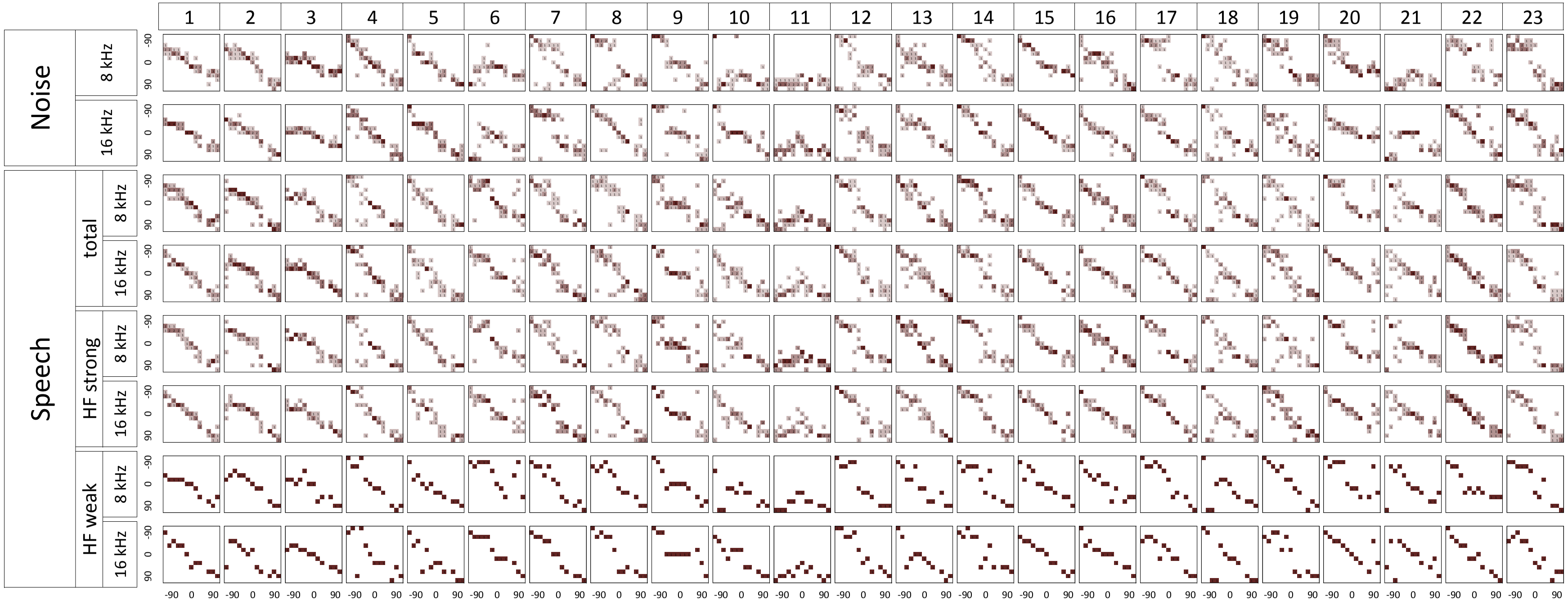


Figure 29. Confusion matrices for HL for Experiment 3. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

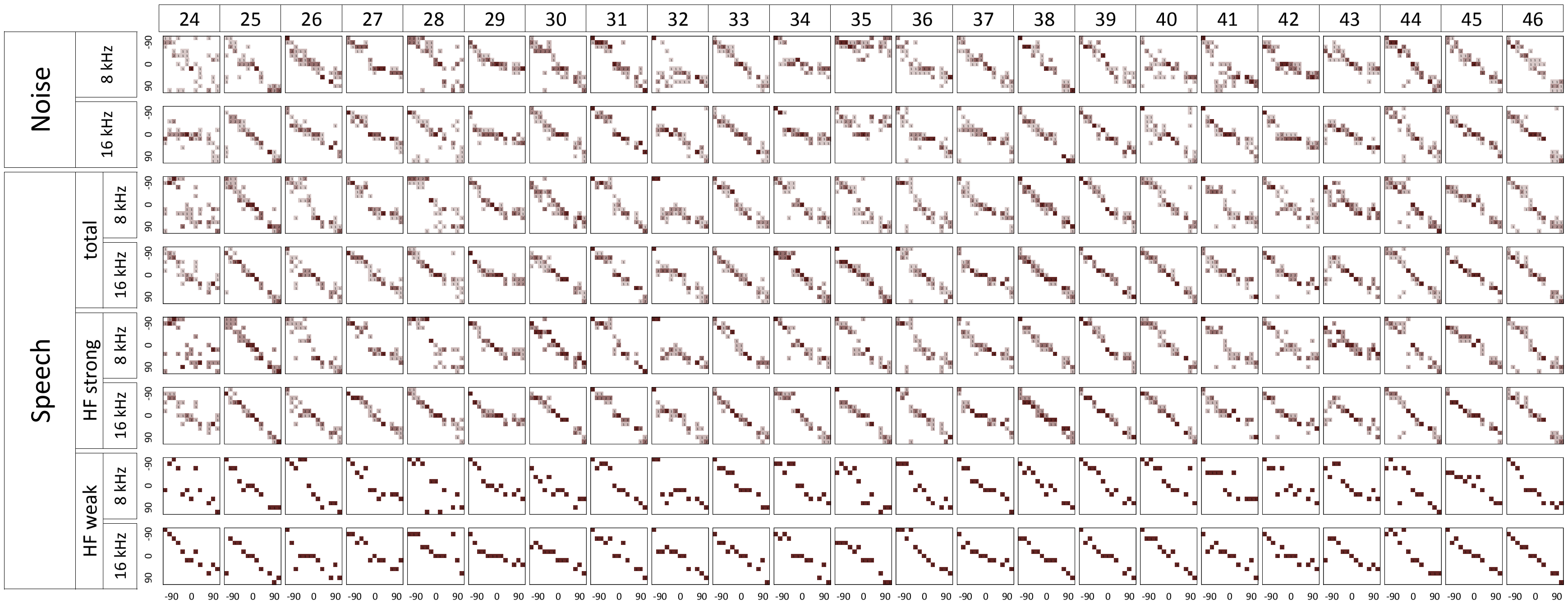


Figure 30. Confusion matrices for NH for Experiment 3. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

Table 5. Mean error of selection (±SD) for five speaker locations for Experiment 3. HL group (Table a) and NH group (Table b).

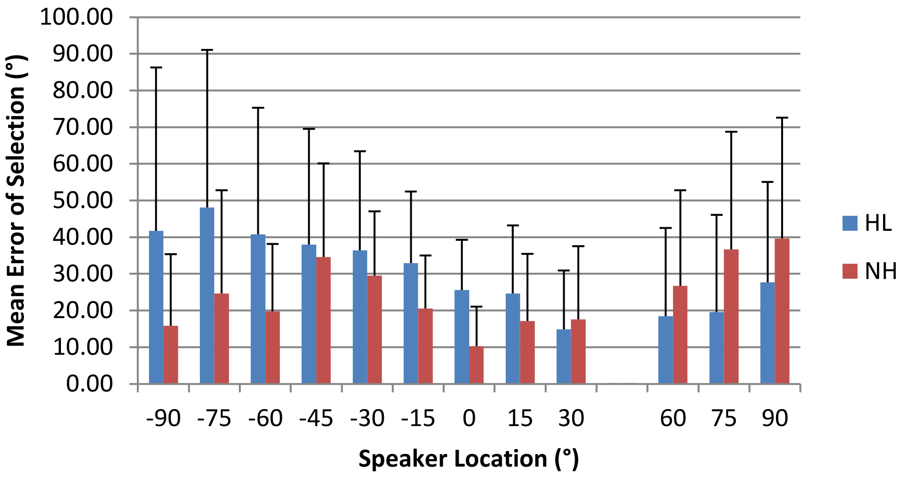
a. Hearing loss participants

		Speaker -90°		Speaker -60°		Speaker 0°		Speaker 60°		Speaker 90°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	41.7	56.2	40.8	42.3	25.6	14.7	18.4	19.0	27.7	15.7
	16 kHz	40.4	56.5	42.4	35.4	10.9	11.0	13.4	10.5	26.6	16.0
Speech Total	8 kHz	32.0	44.0	31.0	35.0	17.1	10.2	13.5	10.5	20.1	12.8
	16 kHz	31.1	41.2	30.7	32.0	13.5	9.0	13.4	12.4	19.4	17.3
Strong	8 kHz	31.3	42.5	30.7	32.6	18.5	10.9	13.0	11.7	19.3	12.4
	16 kHz	29.8	40.0	27.2	30.4	12.4	9.8	13.5	12.0	20.2	20.5
Weak	8 kHz	33.9	51.4	32.0	49.8	13.0	12.2	15.0	18.6	22.2	18.6
	16 kHz	35.2	49.7	41.1	52.2	17.0	15.9	13.0	17.1	17.0	13.0

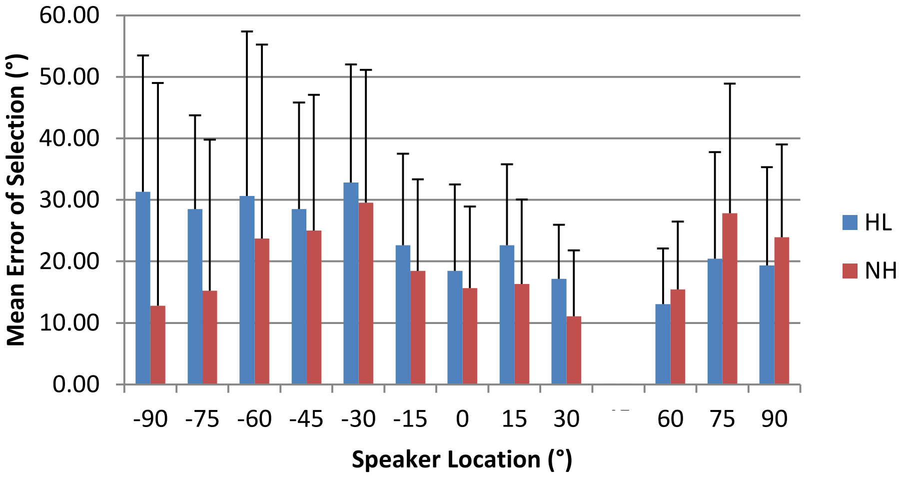
b. Normal hearing participants

		Speaker -90°		Speaker -60°		Speaker 0°		Speaker 60°		Speaker 90°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	15.8	19.5	19.7	18.4	10.3	10.8	26.7	26.0	39.6	33.0
	16 kHz	24.0	34.9	25.3	19.3	3.8	4.7	24.8	22.1	33.8	27.6
Speech Total	8 kHz	13.2	22.2	21.5	23.0	16.0	13.5	15.3	7.8	23.6	14.3
	16 kHz	17.1	21.8	14.5	13.2	2.4	3.7	16.8	14.6	21.7	18.3
Strong	8 kHz	12.8	22.1	23.7	26.7	15.7	14.0	15.4	9.0	23.9	16.0
	16 kHz	15.0	21.1	13.3	11.4	2.2	3.9	16.3	13.0	20.4	19.5
Weak	8 kHz	14.3	25.0	15.0	21.2	17.0	14.5	15.0	11.1	22.8	15.6
	16 kHz	23.5	36.7	18.3	23.0	3.3	6.3	18.3	27.1	25.4	19.9

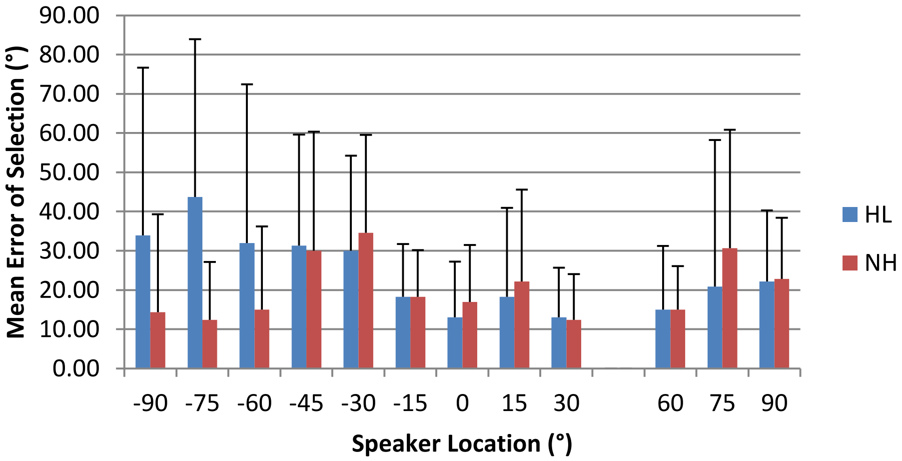
Note. Mean is the mean error of selection in degrees.



a. Noise

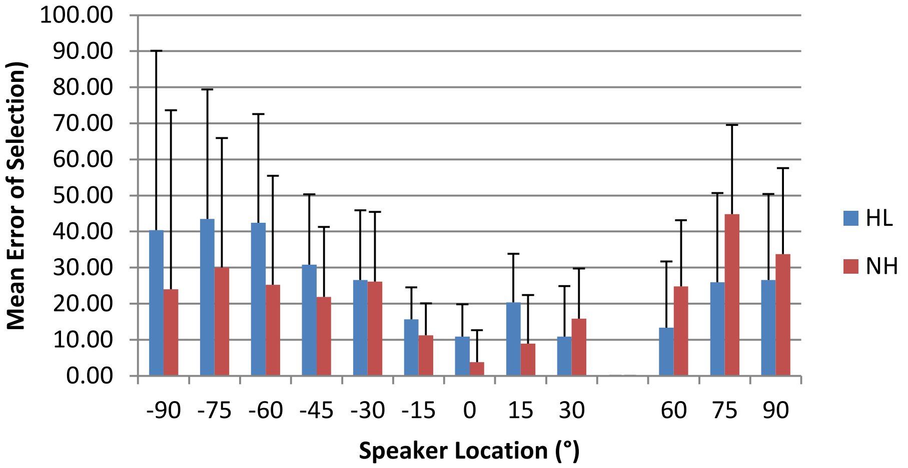


b. Strong speech

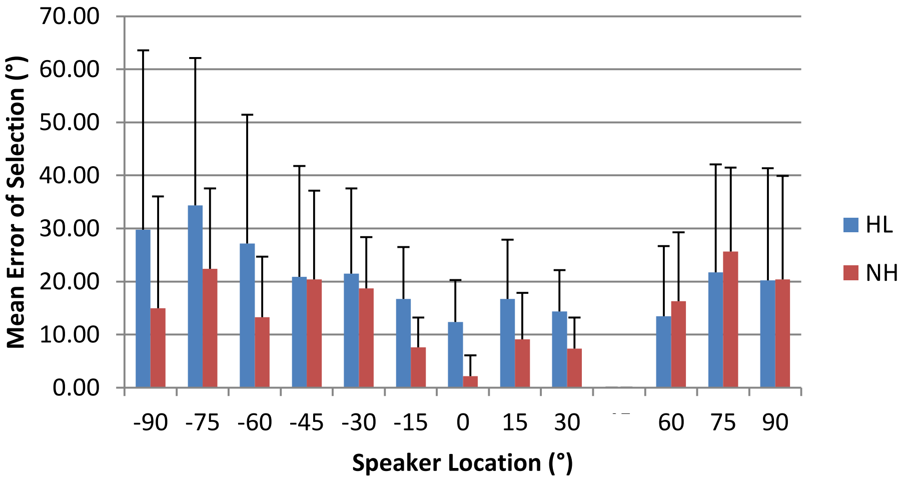


c. Weak speech

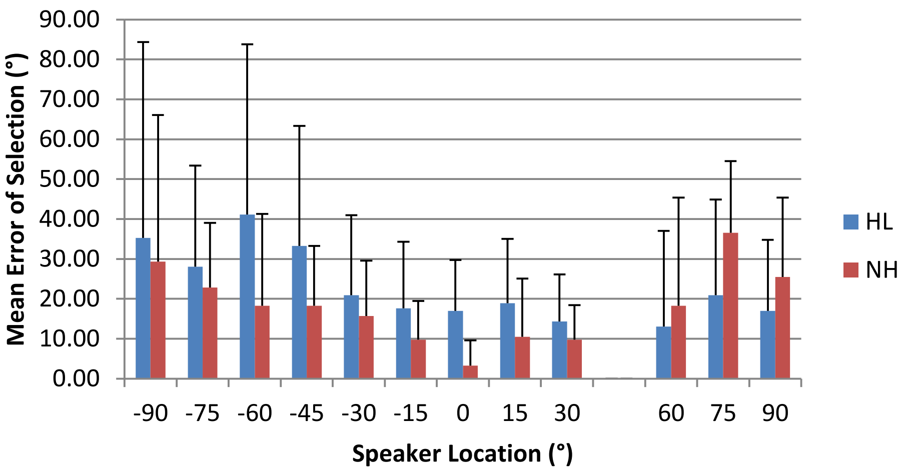
Figure 31. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (noise, strong speech and weak speech) in Experiment 3, for signals in the 8-kHz filter condition.



a. Noise



b. Strong speech



c. Weak speech

Figure 32. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (noise, weak speech, and strong speech) in Experiment 3, for signals in the 16-kHz filter condition.

Table 6. Summary of the four-way analysis of variance for Experiment 3.

Source	Hypothesis *df*	Error *df*	F	P
Hearing (H)	1	44	2.972	0.092
Signal (S)	**2**	**88**	**13.095**	**<0.001***
Frequency (F)	**1**	**44**	**14.591**	**<0.001***
Location (L)	**12**	**528**	**14.586**	**<0.001***
H x S	2	88	0.024	0.934
H x F	1	44	0.004	0.95
H x L	12	528	3.802	0.11
S x F	2	88	1.271	0.286
S x L	24	1056	1.4	0.217
F x L	**12**	**528**	**6.364**	**<0.001***
H x S x F	2	88	1.704	0.189
H x S x L	24	1056	1.188	0.314
H x F x L	**12**	**528**	**1.953**	**0.027***
S x F x L	24	1056	1.491	0.132
H x S x F x L	24	1056	1.623	0.09

Note. Significance level is 95%. Data showing a significant difference is marked with a bold font and asterix.

3.4 Experiment 4. Lateral Vertical Plane

Figures 33 and 34 display the confusion matrices for the individual participants for all stimuli and frequency conditions for Experiment 4. For this experiment the angle ranges from speaker location 0°, which is directly below the participant, to speaker location 180° which is directly above the participants head. Speaker location 90° is found at the level of the participant's right ear. While visual assessment of the confusion matrices for Experiment 4 suggest the overall localization ability in this plane is more accurate than Experiment 3 (refer to Fig 29 and 30), which is in the same vertical plane, there are some participants such as 11 in the HL group for speech stimuli and 35 in the NH group for the noise conditions who demonstrate some particularly large errors.

Descriptive statistics and an illustration of trends for the participants can be found in Table 7 and Figures 35 and 36. Examination of the four way ANOVA (see Table 8) shows there was no significant main effect of hearing type on mean error of selection $F(1, 44) = 1.031$, $p = .315$; however significant main effects were found for frequency filter type (8 kHz compared to 16 kHz) $F(1, 44) = 7.656$, $p < .05$ and speaker location $F(12, 528) = 9.497$, $p = < .001$.

However, the significant interaction between hearing type and signal type, $F(2,44) = 5.847$, $p = .009$) demonstrates that there is a difference in the effects of the different signal types for the two hearing groups. The pairwise comparisons show that although there is no difference between the two hearing groups for noise ($p > .05$), the NH group localize significantly better than the HL group in both the speech strong and speech weak conditions ($p < .05$). For example at speaker location 0°, the strong speech mean at 8 kHz is 19.1° ± 27.4 for the HL participant, whereas the equivalent NH result is 11.1° ± 32.0. A second example is for speaker location 30° with speech weak 16 kHz where the HL participant has a mean error of selection of 12.4° ± 25, and the NH has a mean of only 3.9° ± 6.7.

As stated, a significant difference in mean error of selection between the 8 kHz filtered frequency and the 16 kHz filtered frequency was found $F(1, 44) = 7.656$, $p < .008$) for Experiment 4. While the results are not always consistent amongst participants, the mean error of selection for the 16 kHz sound condition is generally lower than the 8 kHz sound condition for both the HL and NH groups. Several examples of this are HL speaker location 90° for noise with the mean error of selection for 8 kHz 15°± 7.6 and the 16 kHz mean of 7.5° ± 6.3. A NH example is that for speaker location 0° with strong speech; the 8 kHz mean is 11.1° ± 32, and the 16 kHz mean is 5.9° ± 6.3.

Overall, the localization appears less affected by speaker location compared to the other experiments, but the effect of location is still significant ($F=9.497$, $p<0.001$). Like Experiment 3, but to a lesser degree, the HL participants do tend to make more mean localization errors for the lower speakers (0° and 15° locations) compared to the higher speakers (165° and 180° locations). For example, for 16 kHz strong speech, the mean error is 18.3° ± 25.6 (for speaker location 0°) compared to 2.0° ± 2.9 (for speaker location 180°) which indicates a typical difference. In the 8 kHz noise condition, the HL participants also have a large variation mean error; the standard deviation reaching as high as ± 17.7 for speaker location 150°.

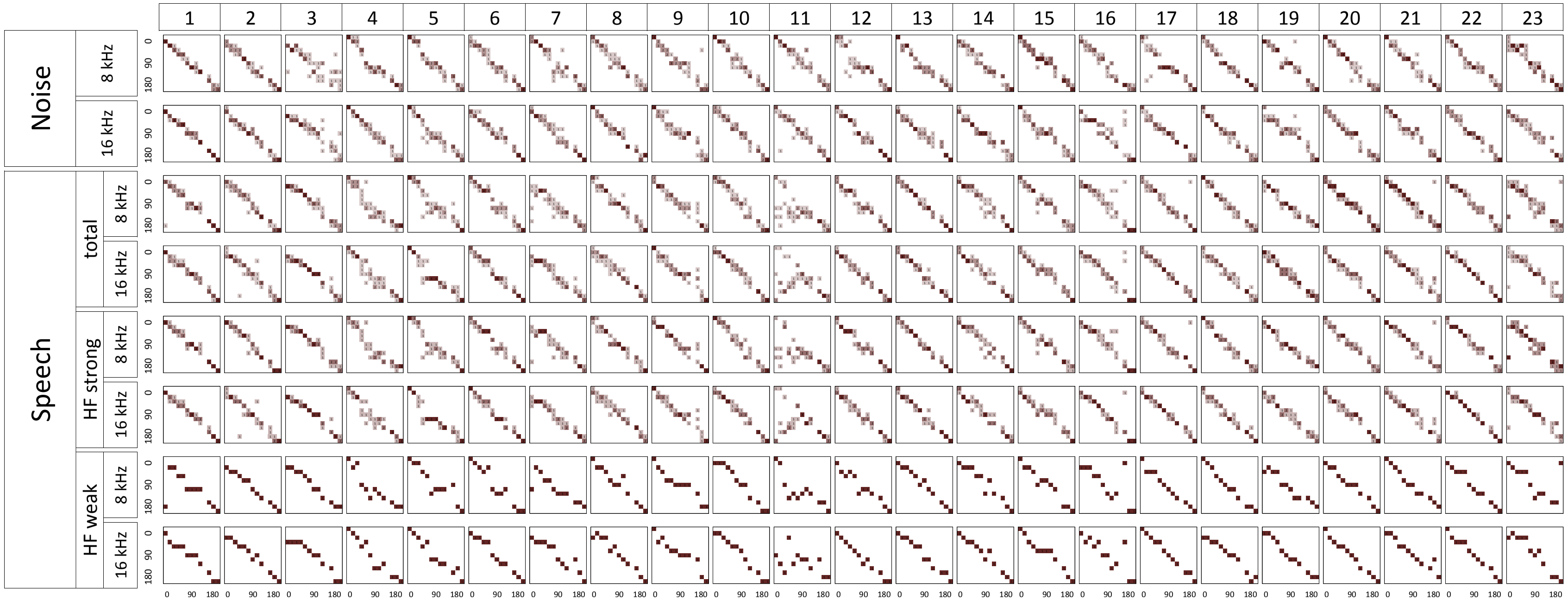


Figure 33. Confusion matrices for HL for Experiment 4. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

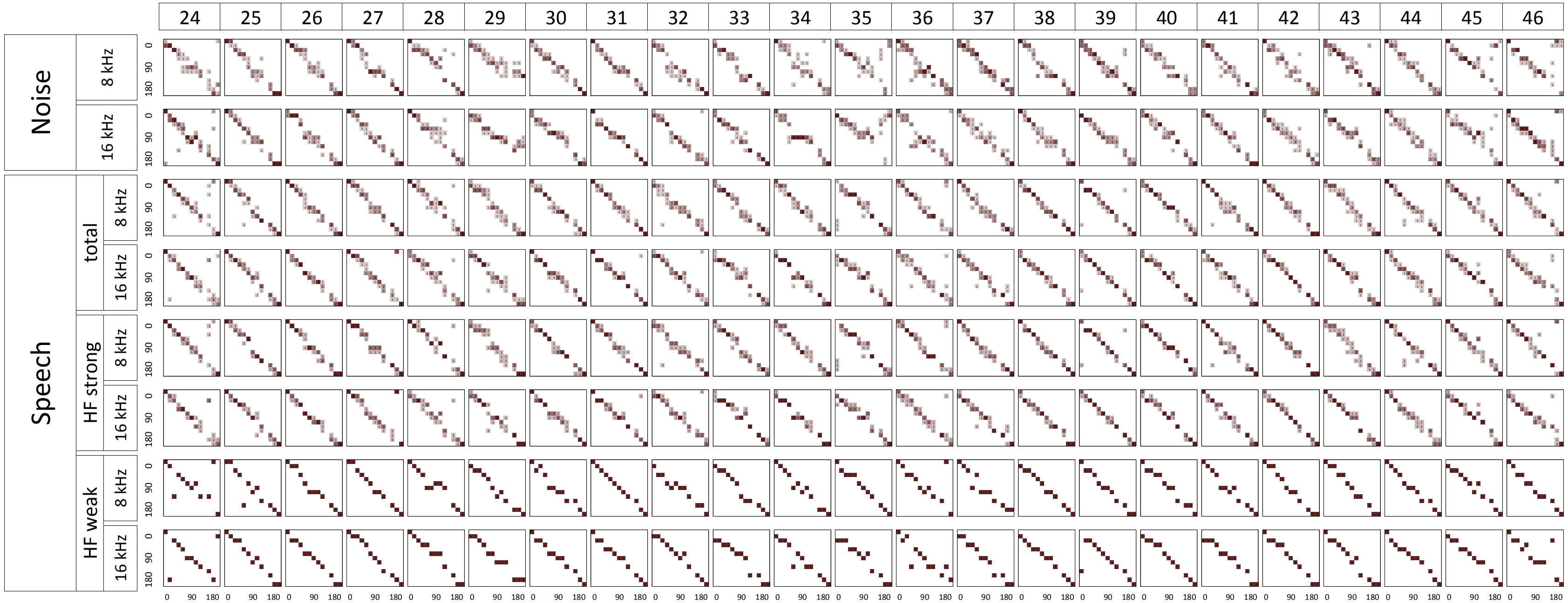


Figure 34. Confusion matrices for NH for Experiment 4. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

The significant interaction between hearing status and location confirms that there was a difference in localization performance between the two groups, but that this relationship changes depending on speaker location. Examination of the post hoc pairwise comparisons shows that at the lower speaker locations, the NH group have a better localization performance than the HL group ($p < .05$). For example the HL mean error of selection at speaker location 0° (speech strong 16 kHz) was 18.3° ± 25.6, but for the NH group the mean error was 5.5° ± 6.3. At the higher speaker locations e.g. 165° and 180°, it was the NH group that had the poorer localization performance. A particularly obvious example was for noise 16 kHz at speaker location 180° where the mean error of selection for the HL group was only 4.1° ± 5.4, but the NH group had a mean error of selection of 20.5 ° ± 41. It was also interesting to note the high level of standard deviation with the NH participants, indicating that there was a large amount of individual variation in localization performance in the higher speaker locations. For example, for NH speaker location 180° for noise 8 kHz, there was a standard error of ± 41 which is high compared to the equivalent HL standard error of ± 5.4

The localization ability of the participants also varied according to a significant interaction between speaker location and signal type F(24, 1056 =1.891, $p = .006$). At speaker location 0°, it is noise that is localized better than either type of speech. This is demonstrated in the HL group with noise 16 kHz having a mean error of selection of 9.1° ± 8.3, whereas the speech strong and speech weak have means of 18.3° ± 25.6 and 18.3 ± 20.2 respectively. However, in the middle and upper speaker locations noise has the poorest localization mean, and generally speech strong is the best. An example of this is from the NH group at speaker location 90°, where noise 8 kHz has a mean of 14.0° ± 9.3, speech strong 9.6° ± 5.4 and speech weak 11.1° ± 9.3.

Finally, there is a significant interaction between frequency and location $F(12, 528) = 3.629$, $p < .05$). The pairwise comparisons confirm that speaker location 0° and 15° for the 8 kHz frequency has a lower mean error of selection compared to the 16 kHz frequency. At speaker location 15° this difference is significant (p < .05). However, for speaker locations 60°, 75° and 90° there is significantly better localization for the 16 kHz frequency e.g. speaker 90° NH speech strong, the mean errors of selection for the 8 kHz and 16 kHz are

9.6° ± 5.4 and 2.6° ± 3.3 respectively. At the higher speaker locations, above 120°, there is no difference in localization ability between the 8 kHz and 16 kHz conditions.

Table 7. Mean error of selection (±SD) for five speaker locations for Experiment 4. HL group (Table a) and NH group (Table b).

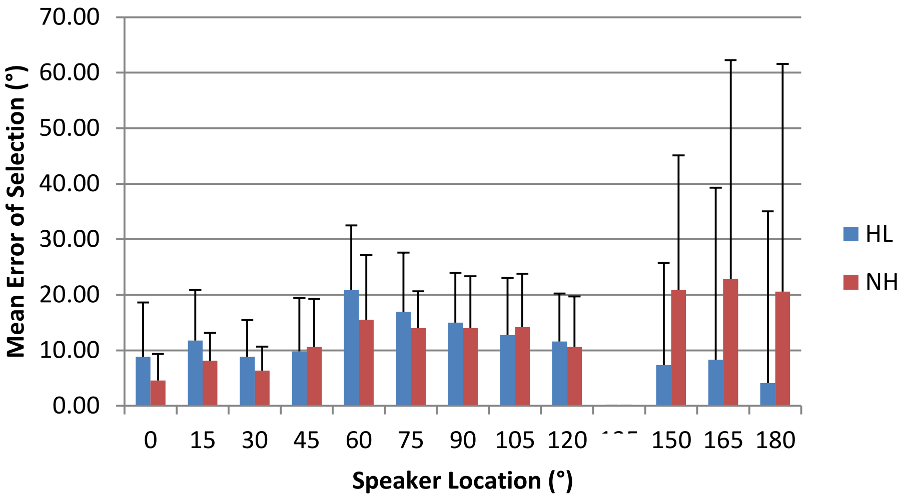
a. Hearing loss participants

		Speaker 0°		Speaker 30°		Speaker 90°		Speaker 150°		Speaker 180°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	8.8	12.2	8.8	7.8	15.0	7.6	7.3	4.4	4.1	5.4
	16 kHz	9.1	8.3	8.0	5.3	7.5	6.3	13.7	17.7	3.4	6.1
Speech											
Total	8 kHz	19.9	24.7	8.2	5.0	12.4	8.9	9.1	10.2	5.7	10.5
	16 kHz	18.3	23.6	11.3	17.9	8.5	8.7	10.1	14.5	2.1	3.0
Strong	8 kHz	19.1	27.4	7.2	4.2	11.1	9.8	7.2	7.5	3.9	5.0
	16 kHz	18.3	25.6	10.9	15.8	8.0	8.6	8.5	12.6	2.0	2.9
Weak	8 kHz	22.2	38.9	11.1	13.7	16.3	11.9	15.0	29.7	11.1	34.2
	16 kHz	18.3	20.2	12.4	25.0	9.8	11.6	15.0	24.8	2.6	5.8

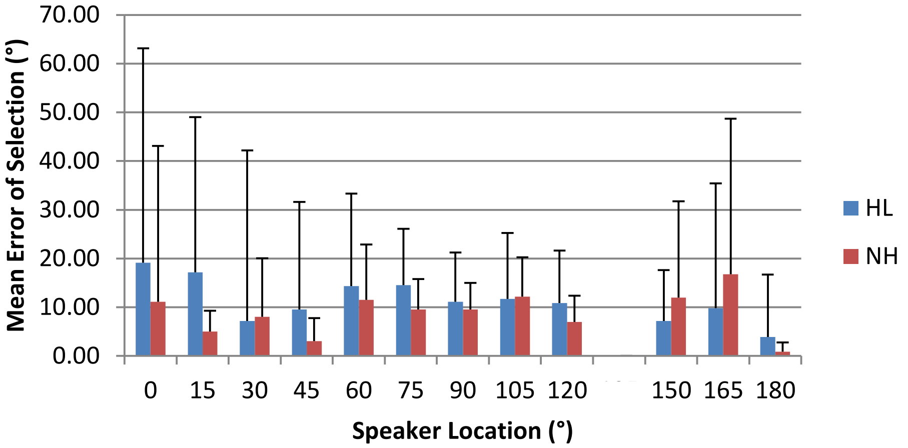
b. Normal hearing participants

		Speaker 0°		Speaker 30°		Speaker 90°		Speaker 150°		Speaker 180°	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Noise	8 kHz	4.6	4.8	6.4	4.3	14.0	9.3	20.9	24.2	20.5	41.0
	16 kHz	7.5	9.7	7.5	4.4	8.6	5.2	12.7	20.4	15.8	38.2
Speech											
Total	8 kHz	9.1	23.9	8.3	10.0	9.9	5.4	10.8	15.5	0.8	1.6
	16 kHz	8.0	9.3	3.6	4.3	2.9	3.2	12.1	20.6	2.9	9.4
Strong	8 kHz	11.1	32.0	8.0	12.0	9.6	5.4	12.0	19.8	0.9	1.9
	16 kHz	5.9	6.3	3.5	4.6	2.6	3.3	12.6	22.0	1.1	2.1
Weak	8 kHz	3.3	6.3	9.1	19.0	11.1	9.3	7.2	8.9	0.7	3.1
	16 kHz	14.3	28.4	3.9	6.7	3.9	6.7	10.4	25.0	8.5	34.4

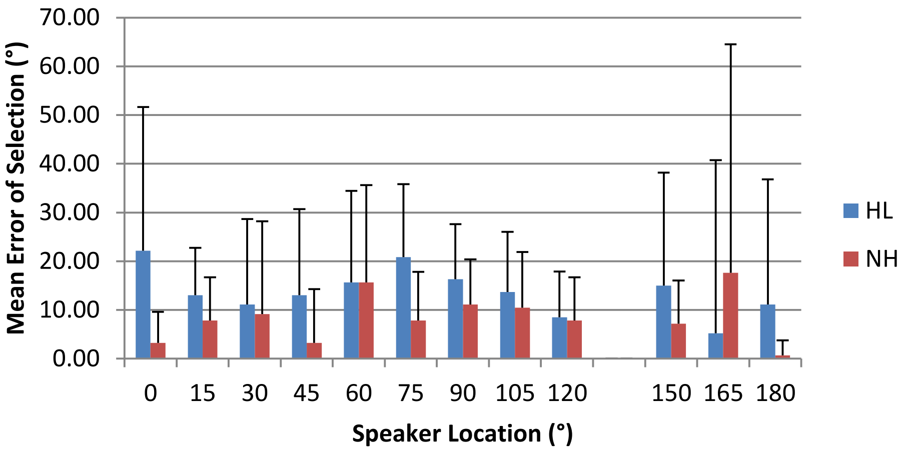
Note. Mean is the mean error of selection in degrees.



a. Noise

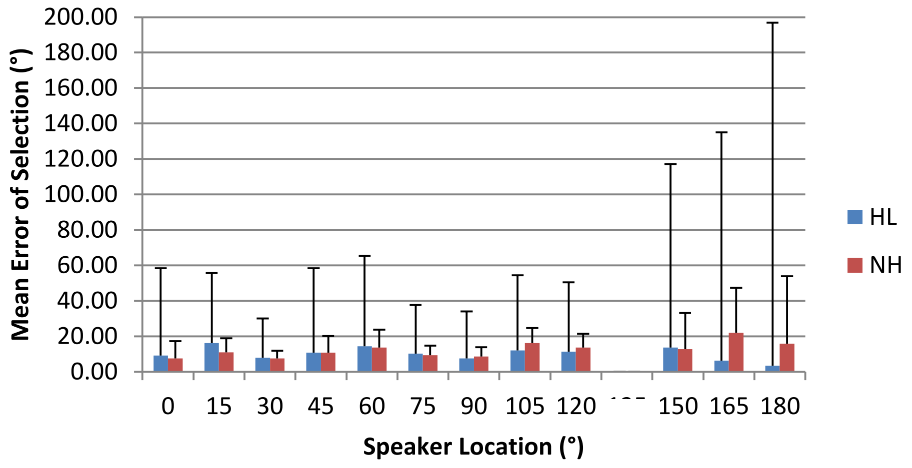


b. Strong speech

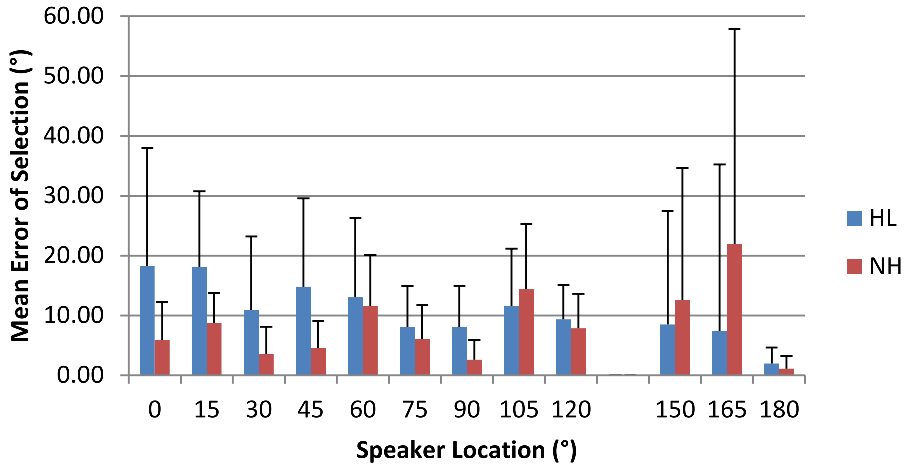


c. Weak speech

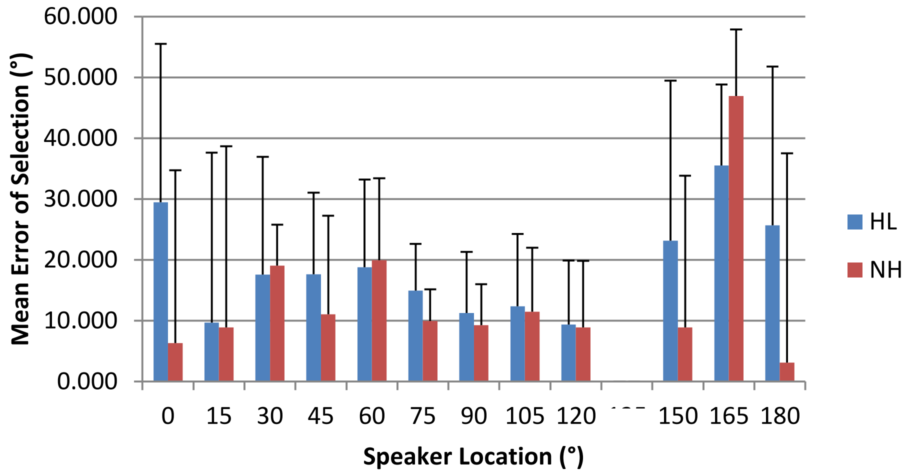
Figure 35. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (noise, weak speech, and strong speech) in Experiment 4, with signals in the 8-kHz filter condition.



a. Noise



b. Strong speech



c. Weak speech

Figure 36. The means and standard deviations for the measures of the extent of error in the HL and NH groups across speaker locations for the three signal types (noise, weak speech, and strong speech) in Experiment 4, with signals in the 16-kHz filter condition.

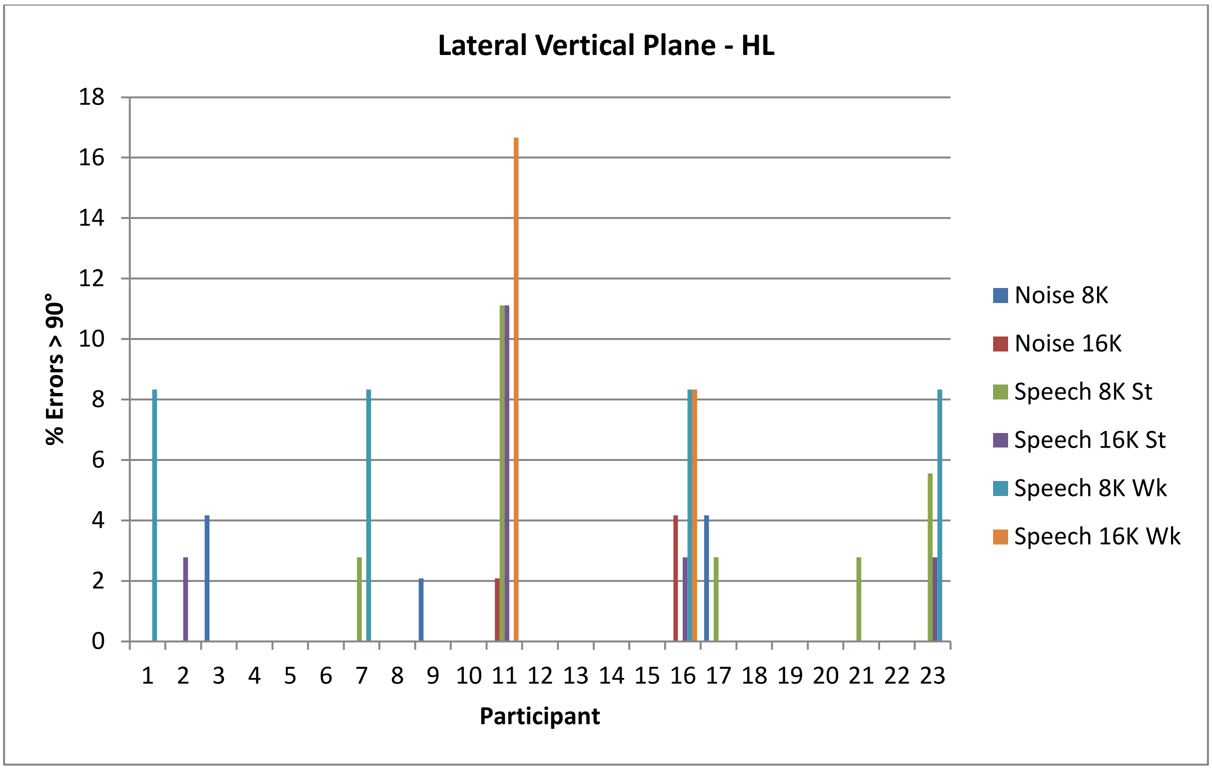
Table 8. Summary of the four-way analysis of variance for Experiment 4.

Source	Hypothesis *df*	Error *df*	F	p
Hearing (H)	1	44	1.031	0.315
Signal (S)	2	88	2.686	0.09
Frequency (F)	**1**	**44**	**7.656**	**0.008***
Location (L)	**12**	**528**	**9.497**	**<0.001***
H x S	**2**	**44**	**5.847**	**0.009***
H x F	1	44	1.012	0.32
H x L	**12**	**528**	**3.982**	**0.001***
S x F	2	88	0.825	0.432
S x L	**24**	**1056**	**1.891**	**0.006***
F x L	**12**	**528**	**3.629**	**0.003***
H x S x F	2	88	1.047	0.35
H x S x L	24	1056	1.191	0.31
H x F x L	12	528	1.224	0.298
S x F x L	24	1056	0.526	0.819
H x S x F x L	24	1056	1.612	0.129

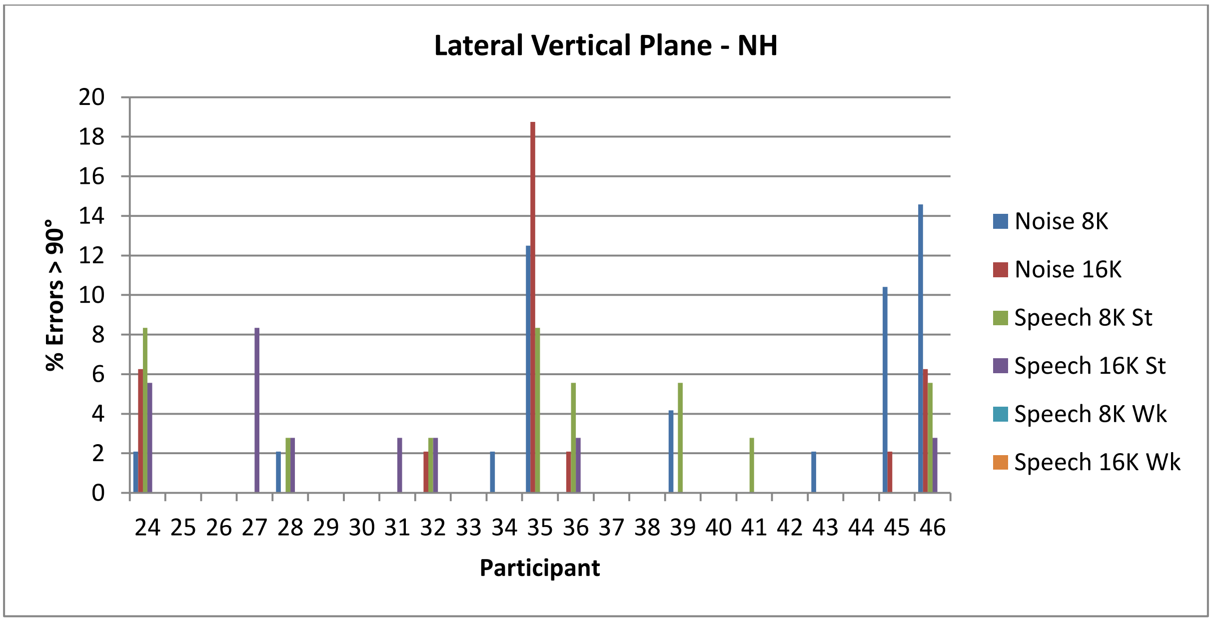
Note. Significance level is 95%. Data showing a significant difference is marked with a bold font and asterix.

3.4.1 Examination of the large errors of selection

As with Experiment 2, there were several participants who displayed errors of selection greater than 90° (see Figure 37). However, there were no clear examples of up/down confusions, which are defined as consistent confusions between the lower speakers (0° and 15°) and the upper speakers (165° and 180°). Possible exceptions included HL participant 11 and NH participant 35 (Refer to Figures 33 and 34). There were no apparent trends of high selection error either between the HL and NH groups or for the other stimuli and frequency conditions. Therefore, from visual observation it appeared there was more precise localization in the lateral vertical plane compared to the lateral horizontal plane.



(a) Hearing loss participants



(b) Normal Hearing participants

Figure 37. Percentage of selection errors made that were greater than 90°. (a) HL participants, (b) NH participants.

3.5 Summary across Experiments

The previous results sections were presented on an experiment by experiment basis. This section will summarise the results and analysis amongst the four different experiments and two hearing types. This section is intended to outline the general trends identified in the analysis across all four experiments. Due to the greatly varied results among the different experimental arrangements only first order interactions will be discussed, and only selected post hoc pairwise comparisons are provided where they are deemed meaningful to addressing the hypotheses.

3.5.1 Hearing status

Results from the five-way mixed model ANOVA conducted on the mean errors of selection revealed a number of significant effects and interactions as discussed below (see Table 10). Overall, there was no significant main effect of hearing status (HL vs. NL) on the ability to localize sound, $F(1,44) = 1.05$, $p = .311$). The mean error of selection for the HL group was 12.2° ± 0.91; the mean error for the normal hearing group was slightly lower at 10.9° ± 0.91 (see table 9).

3.5.2 Experiment type

There was a significant main effect of experiment type (Experiment 1- front on horizontal plane, Experiment 2 – side on horizontal plane, Experiment 3 – frontal vertical plane, Experiment 4 – side on vertical plane) $F(3,132)=50.33$, $p < .001$. The average error of selection for Experiment 1 was lowest (3.3° ± 0.198), and the highest was Experiment 3 with the average error of 20.0° ± 1.258. The mean errors for Experiments 2 and 4 were 12.5° ± 1.67 and 9.9° ± 0.57 respectively. These results demonstrate that localization is more accurate in the horizontal plane with stimuli in front of the participant. Post Hoc pairwise comparisons show that the mean selection error for all experiments is significantly different ($p < .05$), with the exception of Experiments 2 and 4.

3.5.3 Frequency

Overall, low pass filtered noise at 16 kHz (mean error of selection 10.9° ± 0.653) was found to allow more significantly precise localization than 8 kHz noise (mean error of selection 12.2° ± 0.653). This difference was found to be significant $F(1, 44) = 28.34$, $p < .001$) showing that the participants localize better with a greater bandwidth.

3.5.4 Signal Type

There was also a significant main effect for mean error of selection for the signal types, $F(2, 88) = 3.579$, $p < .001$.: i) noise (14.3° ± 0.814); ii) speech strong (9.8° ± 0.681); and iii) weak speech (10.59° ± 0.693) ($F(2, 88) = 33.58$, $p = <0.001$). Bonferroni pairwise comparisons confirm that all signal types are significantly different from each other (p < .05). This result suggests that strong speech improves localization ability of participants compared to the other signal conditions of noise or speech with weaker HF content.

3.5.6 Speaker location

The different experiments had different planes of orientation of the speakers with Experiments 1 and 2 having a horizontal plane (-90 to + 90 degrees) and Experiments 3 and 4, a vertical plane (0 to 180 degrees). Despite these differences in experimental set up, it was found there was a significant difference between the mean errors of selection with location of the speaker of the plane $F(12, 528) = 23.00$, p < .001). As discussed earlier in the results section, the most accurate localization occurs with the middle speakers in the range 6, 7 and 8 (e.g. Experiment 1, speaker locations -30°, 0° and 30°). Overall these speaker locations (6, 7, 8) have a mean selection of error of 8.4° ± .412, 7.0° ± 0.366, and 10.8° ± 0.570 respectively. These are generally lower than the results for the peripheral speakers for example, 2 and 13, which have mean errors of selection of 14.5° ± 1.245 and 21.1° ± 2.595. Further results of the Bonferroni post hoc pairwise comparisons for location are found in Appendix 5. These comparisons show that while speaker 1 is not significantly different from the other speakers, other periphery speakers have a significantly different result to the middle speakers e.g. speaker location 2 vs speaker location 6 ($p < .001$) and speaker location 7 ($p < .001$), and speaker location 13 vs speaker location 6 ($p < .001$).

3.5.7 Interactions between experimental parameters

No significant interactions were found between participant group and experiment number $F(3, 132) = 1.098$, $p = 0.352$), filter frequency $F(1, 44) = .056$, p = -.813), or signal type, $F(2, 88) = 0.814$, $p = .387$. However, there was a significant interaction found with respect to the interaction between hearing group and location, $F(12, 528) = 3.030$, $p < .001$. This interaction means that the localization ability of the different groups varies with the location of the sound source. An example of this difference has already been discussed in section 3.2 where there are different mean selection errors at the lower speaker locations between the hearing loss and the normal hearing groups.

Significant interactions were also found between experiment type and signal type, $F(6, 264) = 6.658$, $p < .001$), frequency, $F(3, 132) = 5.105$, $p = .002$), and location, $F(36, 1584) = 15.466$, $p < .001$). This demonstrates that the participant's ability to localize sound produced with the different signal types, frequency and location is affected by localization plane. This is likely explained by the fact that the different experiments vary significantly in set up, e.g. vertical vs horizontal planes, and front and side planes.

There was no significant interaction found between signal type and filter cut-off frequency, $F(2,88) = 0.179$, $p = .0836$. This would suggest that overall there is no improvement in localization ability by varying the sound source to include either weak or strong speech with either the 8 kHz or 16 kHz filtered sound conditions.

Finally, there were significant interactions between sound source location and both signal types, $F(24, 1056) = 4.270$, $p = .002$) and frequency, $F(12, 528) = 3.815$, $p = .001$. This means that there were differences in localization ability of participants depending on the location of the sound source that is affected by both signal type and frequency.

Table 9. Summary of the mean error of selection and standard errors as presented in the post-hoc results across the four experiments.

Source		Mean (°)	SD (°)
Hearing Status (H)	HL	12.3	.910
	NH	10.9	.910
Experiment (A)	Exp. 1	3.2	.198
	Exp. 2	12.6	1.671
	Exp. 3	20.6	1.258
	Exp. 4	9.9	.574
Signal Type (S)	Noise	14.4	.814
	Speech Strong	9.8	.681
	Speech Weak	10.6	.683
Frequency (F)	8 KHz	12.2	.656
	16 kHz	10.9	.653
Location (L)	1	11.9	1.474
	2	14.5	1.245
	3	10.4	1.064
	4	10.1	.869
	5	12.3	.795
	6	8.4	.412
	7	7.0	.366
	8	10.8	.570
	9	11.2	.547
	10	N/A	N/A
	11	14.6	1.385
	12	19.3	2.077
	13	21.1	2.959

Table 10. Summary of the five-way mixed model analysis of variance performed on the error of selection across the four experiments.

Source	Hypothesis *df*	Error *df*	F	p
Hearing Status (H)	1	44	1.05	0.311
Experiment (A)	**3**	**132**	**50.33**	**< 0.001***
Signal Type (S)	**2**	**88**	**33.579**	**< 0.001***
Frequency (F)	**1**	**44**	**28.34**	**< 0.001***
Location (L)	**12**	**528**	**23.003**	**< 0.001***
H x A	3	132	1.098	0.352
H x S	2	88	0.814	0.387
H x F	1	44	0.056	0.813
H x L	**12**	**528**	**3.030**	**< 0.001***
A x S	**6**	**264**	**6.658**	**< 0.001***
A x F	**3**	**132**	**5.105**	**0.002***
A x L	**36**	**1584**	**15.466**	**< 0.001***
S x F	2	88	0.179	0.836
S x L	**24**	**1056**	**4.270**	**0.002***
F x L	**12**	**528**	**3.815**	**< 0.001***
H x A x S	6	264	1.408	0.212
H x A x F	3	132	0.527	0.664
H x A x L	36	1584	1.282	0.123
H x S x F	2	88	1.119	0.331
H x S x L	24	1056	0.828	0.516
H x F x L	12	528	0.510	0.909
A x S x F	6	264	1.302	0.257
A x S x L	**72**	**3168**	**2.105**	**< 0.001***
A x F x L	**36**	**1584**	**3.766**	**< 0.001***
S x F x L	24	1056	0.899	0.604
H x A x S x F	6	264	1.458	0.193
H x A x S x L	72	3168	0.853	0.807
H x A x F x L	**36**	**1584**	**1.688**	**0.007***
H x S x F x L	**24**	**1056**	**1.717**	**0.017***
A x S x F x L	**72**	**3168**	**1.530**	**0.003***
H x A x S x F x L	**72**	**3168**	**1.890**	**< 0.001***

Note. Significance level is 95%. Data showing a significant difference is marked with a bold font and asterix.

3.6 Different Error Types

3.6.1 Different error types displayed on the confusion matrices

While there was a large amount of variation in localization ability among participants, a visual analysis of individual results from the confusion matrices for both the HL and NH groups indicated that there appeared to be several different types of selection error trends (see Figures 39 – 41). Firstly, a normal presentation and selection error matrix is shown in Figure 38. The presentation angle is on the x-axis and the selection angle on the y-axis. If there was 100 percent accuracy, the matrix would have a negative gradient of -1 and all four replicates would be within the same square. It can be seen from the normal error matrix that for presentation angles 0° to 45° there is good accuracy. From presentation angle 60° to 180° there is a small amount of deviation. Note that there is no result at 135° as this was the dummy speaker.

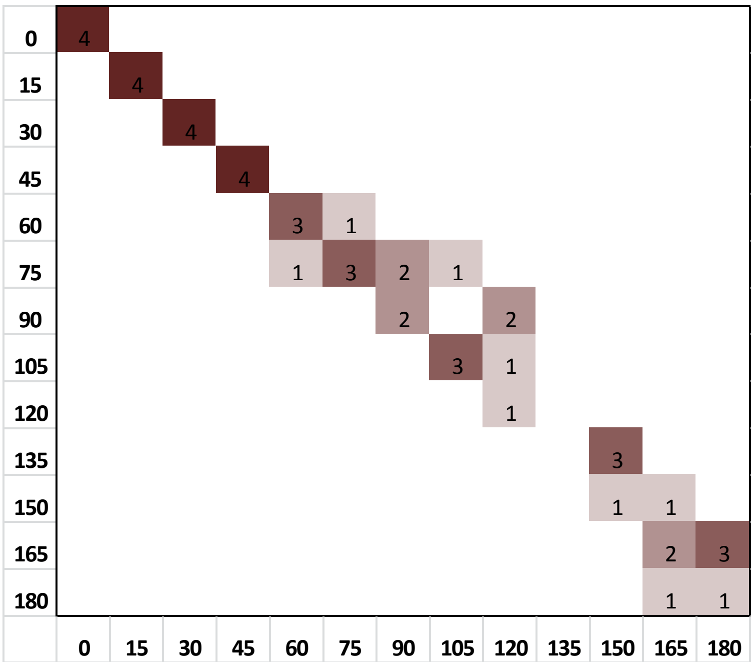


Figure 38. An example of a 'normal' error matrix from HL Participant 8, Noise 8 kHz, Experiment 2. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

Front/back errors occur when the participant has good localization in the speaker range 0° to 90°; however as the presentation angle increase toward the rear i.e. presentation angle 105° to 180°, the participant perceives the sound as coming from the front rather than the rear. A good example of this is the confusion matrix HL participant 3 noise 8 kHz (Figure 39).

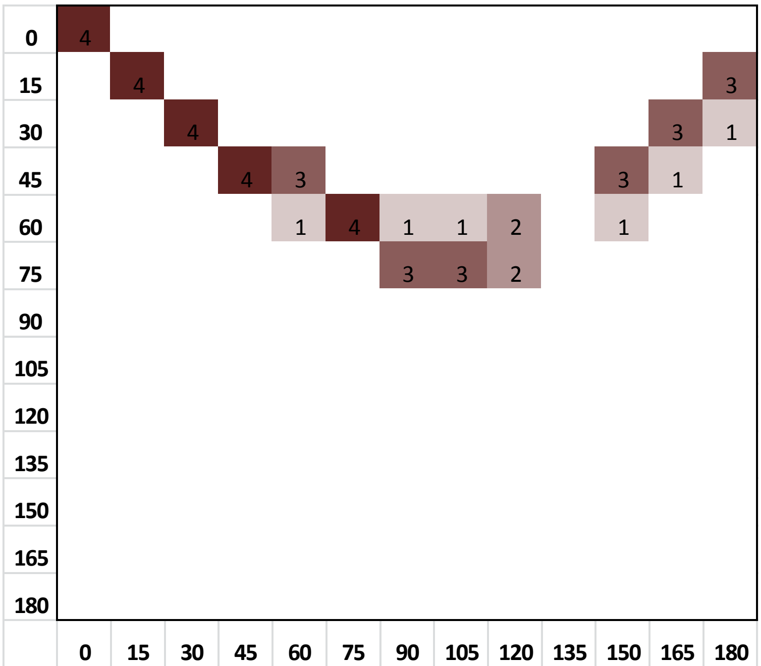


Figure 39. An example of a front/back error matrix from HL participant 3, noise 8 kHz, Experiment 2. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

There are further examples of front/back errors for some participants, particularly in Experiment 2. For NH participants 26 and 34 it was for the noise conditions only, whereas for NH participants 29, 42, and 43 it was for all of the conditions. To a lesser extent, this error was also made in Experiment 4 with the 16 kHz noise stimuli by participant 35. Although not one of the research questions it was interesting to note, all of these participants were female, with the exception of participant 35. These errors were also made by the HL participants in Experiment 2, for participant 3 for the noise conditions, participant 20 for all conditions and participants 21 and 22 for the noise conditions only. All of the hearing loss participants displaying this trend were male with the exception of number 3.

However, further visual examination of the error matrices has indicated that there are two further normal and front/back combinations. These have been termed front/back type A and front/back type B error matrices. A type A error matrix combines a normal matrix pattern with a typical front/back matrix. An example of this is figure 40. There is accurate localization from 0° - 90°, then mixture of normal and front/back in the range 90° - 180°.

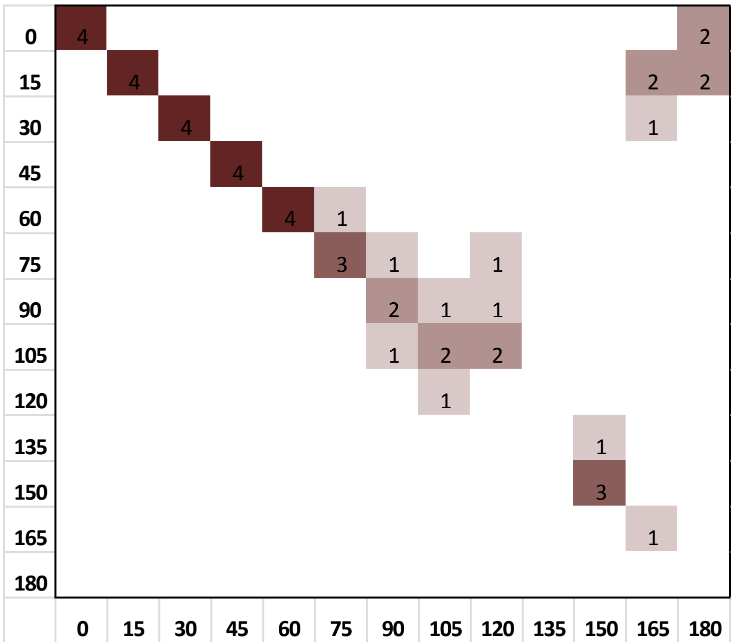


Figure 40. An example of a type A error: A combination of normal and front/back error matrix from HL participant 22, speech total 8 kHz, Experiment 2. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

A type B matrix error differs from a type A matrix error in that it is in the range 0° to 90° where there is the combination of normal and front/back errors and the participant has relatively accurate localization in the range 105° to 180°. An example of this is HL participant 12 noise 8 kHz (Figure 41).

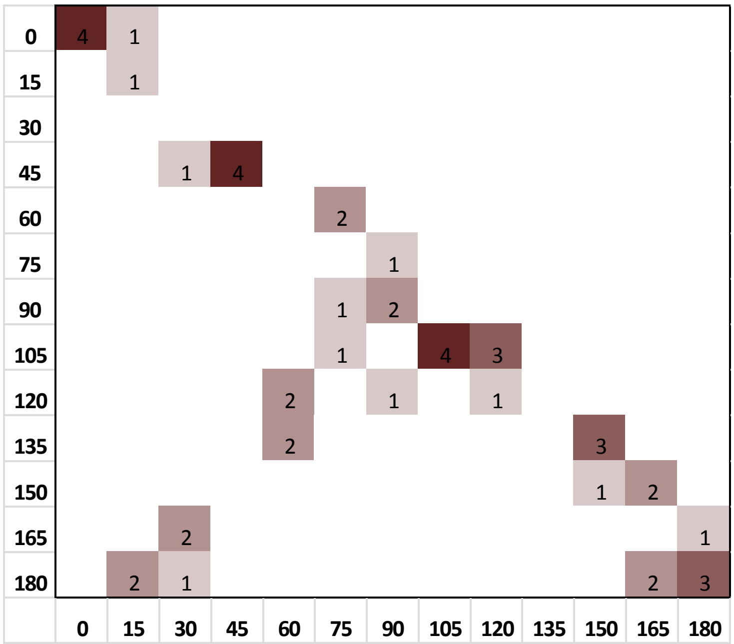


Figure 41. An example of a type B error. A combination of normal and front/back error matrix from HL Participant 12 Noise 8 kHz, Experiment 2. The angle of presentation is on the x-axis and angle of selection is on the y-axis.

Visual examination of the error matrices for the vertical experimental planes, as in Experiments 3 and 4, suggest that up/down errors are less common across all noise, speech and frequency conditions for both the HL and NH groups of participants. One possible example of a type A error is for NH Experiment 4 participant 35 for noise in both 8 kHz and 16 kHz conditions.

3.3.2 Examination of large errors of selection

Large errors of selection have been defined by Best et al. (2005) as individual results that have an error of greater than 90° between presentation and selection angles. As stated previously, Experiment 1, (frontal horizontal plane) did not have any large errors of selection for either HL or NH participants due to the accurate localization of all participants in this experiment. Therefore analysis of errors in Experiment 1 was not required. It was also decided not to examine Experiment 3 for large errors as there did not appear to be any up/down errors and there were several participants who appeared to not have any correlation between angles of presentation and selection of the stimuli.

The percentage of trials showing selection error greater than 90° for Experiments 2 and 4 are displayed in figure 42. There are more large errors for both the HL and NH groups in the lateral horizontal plane compared to the lateral vertical plane. A two-way ANOVA was conducted between Experiment number and sound stimulus (i.e. frequency and signal type); the results confirming there was a significant difference due to the experiment type ($F(3, 551) = 19.95$, $p < 0.001$) (see Table 11). However, there was no significant difference between stimuli types $F(5, 551) = 0.69$, $p = 0.42$). The significant difference in the percentage mean errors greater than 90° between experiments is probably attributable to the front/back selection errors made by both HL and NH participants in the lateral horizontal plane (Experiment 2). There are no clear up/down errors in the lateral vertical plane for either the HL or NH groups. The higher percentage mean errors greater than 90° for both noise 8 kHz and noise 16 kHz for HL and NH groups in the lateral horizontal plane is due to the relatively higher number of front/back errors compared to the other noise and frequency conditions, however, as stated above this result was not significant.

Table 11. Two-way analysis of variance of the large errors of selection for all experiments.

Source	SS	df	MS	F	P-value
Experiment	**2098.037**	**3**	**699.3457**	**18.95752**	**1.09E-11***
Stimulus	324.212	5	64.8424	1.757716	0.119854
Interaction	382.7072	15	25.51382	0.691616	0.793882
Within	19477.99	528	36.89014		
Total	22282.95	551			

Note. Data showing a significant difference is marked with a bold font and asterix.

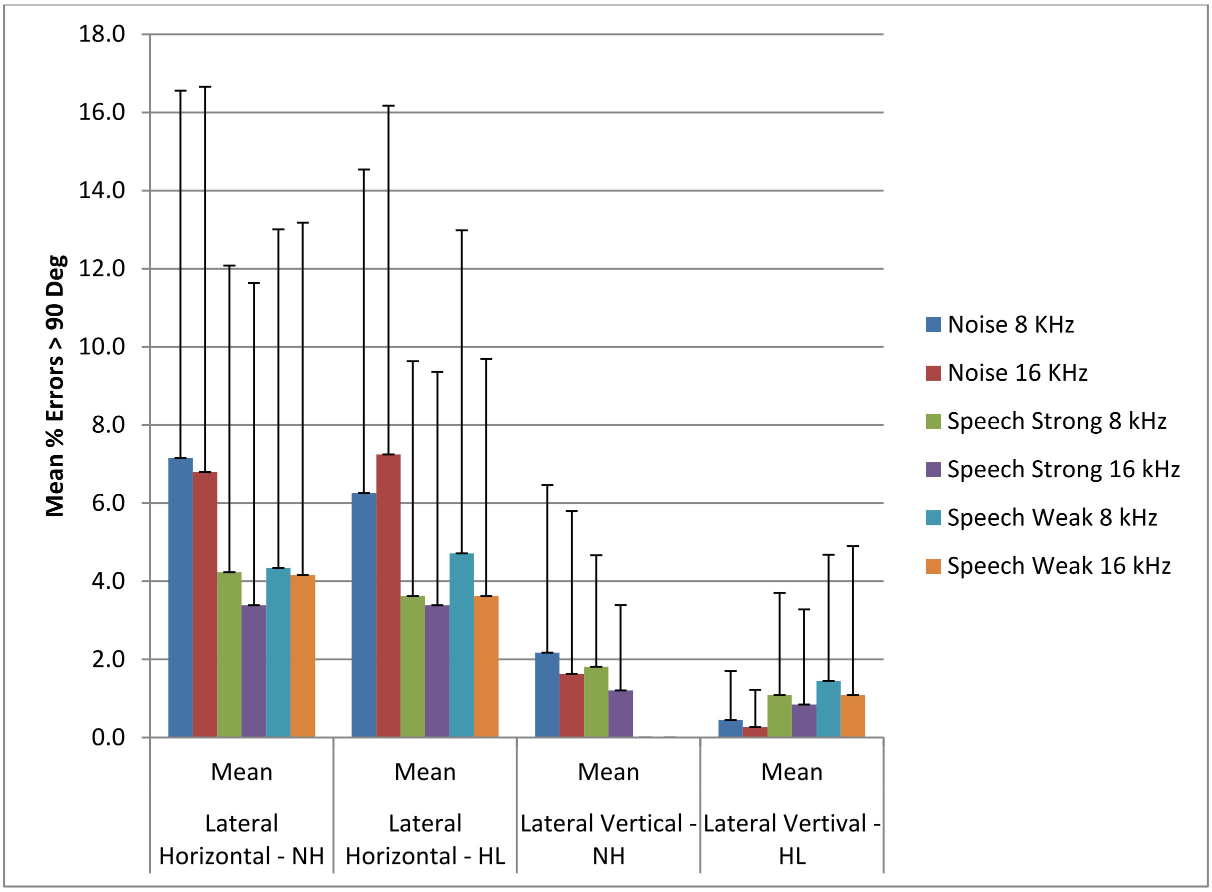


Figure 42. The percentage of errors of selection greater than 90° for Experiment 2 (Lateral horizontal Plane) and Experiment 4 (Lateral vertical plane) for NH and HL participants. Standard deviations shown only in the positive direction.

3.7 Tester Reliability

To ensure that the researcher was accurate in recording the results called out by the participants, on three occasions independent people sat beside the researcher and manually recorded the speaker numbers called out in all four experiments by the participants. The independent persons were not able to see the information being entered electronically by the researcher, but relied only on the voice of the participants. After the experiments were completed, the researcher compared the electronically recorded results with the written independent results. There was 100% accuracy between the two sets of results for all three participants indicating that the researcher was accurate at recording the information from the participants.

3.8 Inter-Ear Comparison

For Experiments 2 (horizontal plane) and 4 (vertical plane) participants were positioned so that their right ears were faced to the speaker array. To determine whether there was a significant effect of test ear on the mean errors, five participants were re-tested in both Experiments 2 and 4 with the left ear facing the speaker array, and then again with the right ear facing the array. This testing occurred independently of the main experiment and the left and rights ears were tested during the same session to ensure that there was not exposure to loud sounds or other adverse stimuli.

A series of Pearson's correlation procedures and paired t tests were conducted on the mean error rate of selection for both ears. Results are summarized in Tables 12 and 13 for the correlations and paired t tests respectively. It was considered that there was a significant effect of the test ear on localization performance if there was a significant effect of ear on selection of error recorded and a lack of a significant correlation between ears.

As shown in Table 11, the selection of error for the left and right ears in Experiment 2 (horizontal) were only significantly correlated, $r(94) = .311$, $0 < .002$ for one of the four participants (N - 45) during the condition when noise was presented as the stimulus. For Experiment 2, the inter-ear correlation was not significant when the signal was strong or weak speech for any subject. Furthermore, a significant between-ear difference on the selection of error in Experiment 2 with noise was found in the HL participant and two of the four (50%) of the NH participants, with the right ear generally showing a higher error than the left ear.

In Experiment 4, the mean error for the left and right ears were not significantly correlated in any of the participants when the signal was strong speech; however when the signal was weak speech, one of the participants (N-45) showed a significant inter-ear correlation. When the signal was noise, three out of five participants (60%) showed a significant inter-ear correlation. Amongst participants who failed to show a significant inter-ear correlation, two (2/5 = 40%) in the strong speech condition, one (1/4 = 25%) in the weak speech condition, and one (1/2 = 50%) in the noise condition showed a significant inter-ear difference.

In summary, a greater inter-ear agreement on the degree of errors was found in Experiment 4 (vertical) compared to Experiment 2 (horizontal). Overall, the right ear showed a greater degree of error than the left ear. This demonstrates the large amount of natural variation in localization ability both among participants and even between individual participant’s left and right ears. An alternative possibility is test-retest variability and given that there is a lot of variability in the mean error of selection this is considered as likely.

Table 12. Results of the Pearson's correlation procedures conducted on the degrees of error for left and right ears for the five participants tested. The equipment set up parameters used were Experiment 2 (a) and Experiment 4 (b).

(a) Experiment 2 (Horizontal)

Participant Number	Speech-Strong			Speech-Weak			Noise		
	n	r	p	n	r	p	n	r	p
1	**72**	**0.043**	**0.723**	**24**	**0.079**	**0.714**	**96**	**0.104**	**0.315**
14	**72**	**0.118**	**0.322**	**24**	**0.273**	**0.197**	**96**	**0.187**	**0.068**
25	**72**	**0.217**	**0.067**	**24**	**-0.055**	**0.800**	96	0.311	0.002*
45	**72**	**-0.024**	**0.844**	**24**	**0.049**	**0.818**	**96**	**0.143**	**0.166**
46	**72**	**0.168**	**0.158**	**24**	**-0.083**	**0.699**	**96**	**0.117**	**0.254**

(b) Experiment 4 (Vertical)

Participant Number	Speech-Strong			Speech-Weak			Noise		
	n	r	p	n	r	p	n	r	p
1	**72**	**-0.079**	**0.509**	**24**	**-0.129**	**0.548**	**96**	**0.169**	**0.100**
14	**72**	**0.113**	**0.345**	**24**	**0.333**	**0.111**	96	0.560	< 0.001*
25	**72**	**0.008**	**0.949**	**24**	**0.202**	**0.345**	**96**	**-0.038**	**0.714**
45	**72**	**0.164**	**0.168**	24	0.454	0.026*	96	0.212	0.038*
46	**72**	**0.066**	**0.582**	**24**	**0.035**	**0.871**	96	0.552	< 0.001*

Note. Data showing a lack of a significant inter-ear correlation is marked in bold font and significant correlations are indicated by an asterisk.

Table 13. Results of the paired t-tests conducted on the degrees of error for left and right ears. The equipment set up parameters used were Experiment 2 (a) and Experiment 4 (b).

(a) Experiment 2 (Horizontal)

Participant Number	Speech-Strong			Speech-Weak			Noise		
	n	r	p	n	r	p	n	r	p
1	71	-1.711	0.091	**23**	**-2.145**	**0.043***	95	-0.564	0.574
14	**71**	**-2.249**	**0.028***	**23**	**-2.635**	**0.015***	**95**	**-2.358**	**0.020***
25	**71**	**-9.028**	**< 0.001***	**23**	**-5.346**	**< 0.001***	**95**	**-8.408**	**<0.001***
45	**71**	**-4.187**	**< 0.001***	23	-0.380	0.707	**95**	**-15.88**	**<0.001***
46	71	-1.175	0.244	23	-0.526	0.604	95	-0.406	0.686

(b) Experiment 4 (Vertical)

Participant Number	Speech-Strong			Speech-Weak			Noise		
	n	r	p	n	r	p	n	r	p
1	**71**	**-2.46**	**0.016***	23	-1.486	0.151	**95**	**-3.039**	**0.003***
14	71	-1.029	0.307	**23**	**-2.798**	**0.010***	**95**	**-4.144**	**<0.001***
25	71	0.000	1.000	23	-0.901	0.377	95	1.858	0.066
45	**71**	**-3.071**	**0.003***	23	-0.440	0.664	**95**	**-1.983**	**0.050***
46	71	-0.656	0.514	23	-1.075	0.293	95	1.302	0.196

Note. Data showing a lack of a significant inter-ear correlation is marked in bold font and significant correlations are indicated by an asterisk.

Discussion

The main aim of the current study was to determine whether there were any significant differences in localization ability of participants with normal hearing (NH group) compared to participants with a hearing loss (HL group), mainly in the extended high frequency range. It was hypothesised that there would likely be no significant difference in localization ability in the horizontal plane (Experiments 1 and 2) due to the dominance of low-frequency binaural cues for localization in this plane, and the expectation that these cues would be audible to both groups of listeners. However, in the vertical plane (Experiments 3 and 4), it was hypothesised that overall, participants with a hearing loss would localize less accurately due to the importance of spectral cues in the high-frequency range for vertical localization. It was predicted that the hearing loss group would have less available extended high frequency information, and potentially that the information they did receive would be more ambiguous given the assumption that hearing loss at these higher frequencies was more likely to be sensorineural.

The comparison of localization performance of the two groups of participants was performed with broadband noise and both strong and weak speech stimuli low-pass filtered at 8 kHz and 16 kHz. It was expected that in the vertical plane (Experiments 3 and 4), all participants would localize more poorly when the stimuli was low- pass filtered at 8 kHz compared to 16 kHz. This is due to the absence of some spectral information from direction-dependent filtering, which has been found to help resolve ambiguities of the auditory system such as the cone of confusion (Best et al., 2005; Carlie et al., 1999; Dobreva et al., 2013; Jin, et al., 2004; King & Oldfield, 1997; Langendijk & Bronkhorst, 2002; Middlebrooks, 1992). As a result, in the 8 kHz filtered conditions it was expected that a greater number of large errors such as up/down and front/back confusions would take place.

An additional aim of the research involved comparing the localization ability across and between the groups for different types of stimuli including broadband noise and speech (with two different levels of high frequency information), speech strong (speech with a large amount of content above 8 kHz) and speech weak (less information above 8 kHz). As stated previously, in the horizontal plane it was not expected there would be any significant difference in localization ability across all participants regardless of group between the two speech and noise stimuli. This expectation was due to the low frequency energy of speech (Gilkey & Anderson, 1995). However in Experiments 3 and 4 (vertical plane), it was hypothesised that the more sporadic high frequency information in the speech due to its time-varying nature-, would make it more difficult for all participants to localize; in particular for the HL participants. Therefore, it was expected there would be more accurate localization of the 16 kHz noise stimuli condition compared to the 16 kHz speech condition. In addition, it was hypothesised that speech with more high frequency content would be more accurately localized due to the greater strength of the pinna information in comparison to the speech with weaker higher frequency content.

4.1 Comparison with other studies

Making comparisons between these results and previous localization studies is complicated due to differences in experimental set up, amount of prior subject training on the task, protocols, stimuli, measures of error and evaluation of the data. Examples of the different methods for the acquisition of participants' responses range from verbal responses (Mason, Ford, Rumsey & De Bruyn, 2001), to using a joystick (Dobreva et al., 2011), nose and head pointing (Best et al., 2005; Giley & Anderson, 1995) headsets (Otte et al., 2013), an extension of their arms (Brungart & Simpson, 2009) and by using a keypad (Yost et al., 2013). However, it is considered that regardless of these differences general trends can be compared.

4.2 Hearing loss and Normal Hearing Participants

4.2.1 Horizontal plane

Although the mean error of selection was slightly lower for the NH participants when compared across all four experiments, indicating better localization than HL participants, this difference was not found to be significant. With respect to the horizontal plane (Experiment 1 – frontal horizontal plane where participants were sitting front on to the speaker array and Experiment 2 where participants were sitting side on), this finding is consistent with the hypothesis and is supported by recent studies which have used participants with high frequency hearing losses and measured thresholds above 8 kHz. For example Otte et al. (2013) did not find significant differences in the accuracy of localization between their younger NH listeners and older HL listeners in the horizontal plane. Dobreva et al. (2011) also found no significant differences between listeners of different ages with the exception of the band 1250 to 1500 Hz, where precision significantly worsened with advancing age.

4.2.2 Vertical plane

The current study showed no overall significant difference of mean error of selection between HL and NH listeners in localization ability in Experiment 3, (speakers were in a vertical position and the participants were sitting front on to the speakers) or Experiment 4 (speakers were in a vertical position and the participants sat side on). However, it is noted that there was significantly poorer localization performance for the HL listeners compared to the NH listeners for the lower speaker positions in both experiments.

Other studies have found greater significance in their results suggesting a high frequency hearing loss does have an impact on localization in the vertical plane. Dobreva et al. (2011) found significantly poorer localization accuracy for the middle aged listeners (who were considered to be most similar in age and hearing loss to the HL participants in the current study) compared to their normal hearing young controls. This difference was found for the conditions of broadband noise with a bandwidth of 0.1 to 20 kHz, high pass filtered noise (3 to 20 kHz bandwidth) and ultra-high pass filtered noise (10 – 20 kHz bandwidth) of 150 ms duration. No significant difference was found for the conditions of low pass filtered noise (0.1 – 1 kHz bandwidth), limited broadband noise (0.1 – 10 kHz bandwidth) and high pass noise (3 – 10 kHz bandwidth). Otte et al. (2013) also found that for their participants with a high frequency hearing loss (averaged for 4, 8 and 11 k Hz) of at least 30 – 40 dB HL, there was significantly poorer localization accuracy compared to their normal hearing listeners for the 150 ms broadband filtered noise conditions of 0.5 to 7 kHz bandwidth, 0.5

to 11 kHz bandwidth and 0.5 to 20 kHz bandwidth. No significant difference was found for the 0.5 to 5 kHz bandwidth condition.

While the current study showed no overall significance difference between HL and NH participants, it is noted a much larger variation was found in responses by all participants in the vertical plane compared to the horizontal plane (Experiments 1 and 2). This greater variability in responses to vertical localization in comparison to horizontal is commonly accepted (Makous & Middlebrooks, 1990) and is similar to Dobreva et al. (2011) and Otte et al. (2013) who found there was greater accuracy of localization in the horizontal planes for all groups of participants. This suggests that the binaural cues are in general more robust in comparison to the pinna cues of the participants with and without a hearing loss. Dobreva et al. (2011) and Otte et al. (2013) differed quite significantly in their design and experimental questions compared to the current study. Dobreva et al. (2011) used an array of speakers that were 10° apart that only extended from -40° to +40° in the vertical plane and a joystick with a laser target for participants to communicate their perceived location of stimuli. The focus of the study was to determine whether there was a difference in localization with age related high frequency hearing loss and central spatial processing deficiencies. Otte et al. (2013) used a motorized arc, which provided a spatial resolution of 2.5° and spanned from -55° to +55° in the elevation. Location of stimuli took place with a head-fixed visual pointer. The localization tasks also occurred in a dark environment and many of the participants were children. The aim of Otte et al.'s study was to determine whether a larger pinna could help compensate for age related high frequency hearing loss. As a consequence of such differences it is not surprising that some dissimilarity were found in the results of the current study.

4.3 Differences between 8 kHz and 16 kHz Filtered Frequency Signals

4.3.1 Horizontal plane

For Experiment 1, the HL participants benefited significantly more from the extra spectral information afforded by the 16 kHz stimuli relative to the 8 kHz filtered stimuli compared to the NH participants. In Experiment 2, no significant advantage was found for the extra information for either group of participants.

It had been hypothesised that there would be no advantage of having the extra information in the horizontal plane and so it was interesting to see that the HL participants benefitted from the extra information in Experiment 1. When examined in more detail, it was the more peripheral speakers (e.g. speaker locations -90°, -75°, 75° and 90°) that showed significant improvement in localization ability with the additional high frequency information. This suggests that at locations essentially opposite the ear, some listeners may make use of frequency information above 8 kHz.

The results are considered to be generally consistent with the recent experiment of Yost et al. (2013) who had a similar set up to Experiment 1 of the current study and measured horizontal localization accuracy of 45 NH listeners in a sound field array of 13 speakers (although speakers 1 and 13 were dummy speakers, not used to overcome edge effects) with 200 ms noise bursts with speakers 15° apart. However, the Yost et al. (2013) study differed from the current study by not including high frequency information above 6000 Hz and more specifically studied differences in localization ability for ITD and ILD conditions with at least 2 octave width filtered noise.

In addition to finding that speakers in front of the participants were localized more accurately than peripheral speakers (like the current study), no significant differences were found in localization ability for the different filtered noise bursts that were divided into filtered conditions of 125 to 500 Hz (ITD condition), 1500 to 6000 Hz (ILD condition) and 125 to 6000 Hz (control condition). Therefore, like the current study (with the exception of the external speakers) frequencies of 8 kHz and above were found not to be required for accurate localization of broadband noise in the horizontal plane. This is consistent with other studies (Best et al., 2005; Middlebrooks, 1992).

4.3.2 Vertical plane

It was found in Experiment 3 there was a significant advantage in having information up to 16 kHz rather than 8 kHz for four of the speakers that were in front of the participants (-30°, -15°, 0° and 15°) for both hearing groups. However there was no advantage for the speakers that were lower or higher than this in elevation. There is some concern that for Experiment 3 in particular, that due to the difficulty of localising the lower and higher speakers the results may be influenced by 'chance' selections or best guesses. This can be seen by the very large standard deviations for many of the lower and higher speaker locations and by the regular comments by participants that they had to do a lot of guessing as they had no idea of stimulus location regardless of frequency filter or stimulus.

In Experiment 4, the trend overall for both hearing groups of participants was for improved localization with the information up to 16 kHz for the majority of the speaker locations. However as for Experiment 3, significance was only found at the speakers that were in front of the participants head (e.g. 60°, 75° and 90°).

These results are considered to be generally consistent with trends found in other research, particularly if the bottom and top speakers were removed as is the case for Otte et al. (2013) and Dobreva et al. (2011) whose speaker arrays did not include the more peripheral speaker locations included in this experiment. While somewhat less comparable due to the far greater number of potential stimuli locations and greater manipulation of the stimuli, the virtual reality studies, generally found more accurate localization occurring with frequencies of 6 kHz and up to 16 kHz due to the additional information from spectral cues being available to the auditory system (Best et al., 2005; King & Oldfield, 1997; Langendijk & Bronkhorst, 2002; Wightman & Kistler, 1991).

4.4 Speech vs Noise

4.4.1 Horizontal plane

Overall, participants were found to localize better in the horizontal plane with strong high frequency content speech, followed by speech with weaker high frequency content and lastly, noise. In Experiment 1, speech was localized significantly better than the noise stimuli, particularly at the peripheral speaker locations. While there was no significant difference between the speech types, the trend was for strong speech to be better localized than weak speech. There were no differences in the localization performance between the hearing groups for this experiment.

In Experiment 2 (lateral horizontal plane), it was only behind the participants at speaker locations 120° – 180° that speech was localized significantly better than noise. The relatively high standard deviations associated with the means at these locations indicate that localization is more difficult for speaker locations behind the participant for both groups of listeners. No difference in localization ability was found between the two different speech types regardless of group.

The finding of the present study that speech is localized better than noise is contrary to the findings of Best et al. (2005) and an earlier study using speech stimuli by Gilkey and Anderson (1995). In Best et al.'s (2005) virtual reality study that compared localization of broadband noise (300 Hz to 16 kHz bandwidth), broadband speech (300 Hz to 16 kHz) and low pass filtered speech (300 Hz to 8 k Hz), it was found in the horizontal plane (lateral angle) that overall there was no significant difference in localization performance in the horizontal (lateral) plane for each stimulus type. Gilkey and Anderson (1995) compared the localization of 25 μs noise clicks to single words in a sphere of dimensions 6.7m x 6.7m x 6.7m containing 239 speakers and also found in the horizontal plane (left/right dimension) that there was no difference in localization ability which is comparable to Experiment 1. In the front/back dimension (which has some similarity to Experiment 2 in that stimuli were presented in front and behind the participants, although there were more speaker locations in the Gilkey and Anderson study), the words were found to be localized significantly worse than the noise clicks.

4.4.2 Vertical plane

In terms of the vertical planes, for Experiment 3, it was found that both types of speech were localized significantly better than noise for both hearing groups. In Experiment 4, the NH group localized significantly better than the HL group for both the strong and weak speech stimuli; however no significant difference between groups was found for the noise stimuli.

Broadband noise has been reported to be the easiest stimuli to localize compared to a number of other stimuli (Carlile et al., 1997). This is due to the broadband noise being more spectrally stable compared to speech and narrowband noise (Butler, 1986; Makous & Middlebrooks, 1990; Middlebrooks, 1992). Therefore, it was expected that noise would be more accurately localized compared to speech stimuli. However, in the current study, even on occasions where the effect was not statistically significant, the trend for speech to overall be localized better was apparent. In comparison, Best et al. (2005) found their normal hearing participants localized significantly more accurately with the broadband noise (300 to 16 kHz bandwidth) compared to the broadband speech (300 to 16 kHz bandwidth) and the poorest localization performance was with the low pass filtered speech (300 to 8 kHz bandwidth). Gilkey and Anderson (1995) also found in the vertical plane that the click trains were localized significantly better than the speech stimuli.

In the current study it is speculated that one potential reason that there was better localization performance for the participants for the speech stimuli was as a result of its longer duration. Best et al. (2005) calculated their average speech stimuli to be an average duration of 710 ms and as the words were from the same list the current study is thought to have a similar average duration compared to the 150 ms noise burst. A possible example of this could be seen in Experiment 2 where for the speakers behind the participant, there was a significantly lower mean error of selection for the speech stimuli compared to noise regardless of frequency content. Therefore, the longer duration of the speech may have given the participants more time to gauge a reference point for where they thought the speech stimuli was being presented which was of greatest use for the more difficult speaker locations.

Another reason the results may have differed from the Best et al. (2005) study was that while the words were from the same phonetically balanced wordlist, a female recorded voice was used, which is likely to contain more high frequency content than a male voice. In addition, when the words in the current study were allocated to speech type i.e. speech strong or speech weak, the words were ordered with respect to high frequency content above 8 kHz. The top 33% of these words were used for the strong speech condition and the bottom 15% of the words with high frequency content above 8 kHz were used for the weak high frequency content condition. Therefore, overall, the current study used words that contained a greater amount of high frequency content.

A further explanation for speech being localized better than noise in the current study was that Best et al. (2005) presented the stimuli over headphones after recording filter functions from the individual participants in order to imitate a more free field situation. As a consequence any movement of the head would not have provided any additional localization cues to the participants. Gilkey and Anderson (1995), also had their participants hold a bite bar to prevent head movement. In the current study, while participants were asked to not move their heads during the presentation of the stimulus and complied well with this request, there may have been the potential for them to do this slightly. Due to the longer duration of speech stimuli compared to noise it is possible that participant head movement allowed for the use of additional cues (Moore, 2007). This was not considered possible with the noise due to its particularly short duration (Carlile et al., 1997; Yost et al., 2013). Attempts were initially made to ensure this did not occur with the use of a chin brace, created with a height adjustable stand. However as it was quite bulky and sat in front of the speakers there were concerns it may interfere with the stimulus from the speakers in front of the participants. A line of fishing twine was also attached and listeners were asked to line up their heads to a marked spot. However, because the arc was quite small, less agile and taller participants struggled to fit themselves around the wire when getting into the proper position and so after one participant slipped and tripped the fishing line was also abandoned.

4.5 Localization Behaviours and Errors

One notable difference in performance for the two groups was that in Experiment 3 and to a lesser extent in Experiment 4, the HL participants tended to underestimate the location of the stimuli increasing the mean error of selection for lower speakers (-90°, -75°, -60°, -45°, -30°, -15°, 0° and 15°) in Experiment 3 and 0°, 15°, 30°, 45°, 60°, 75° in Experiment 4, compared to the results for the NH participants for all stimulus conditions. This indicates that there may be external factors influencing the selection of certain speaker locations. One explanation that may explain this effect is that the HL participants tended to be older, having a mean age of 53.7 ± 9.10 years compared to 24.65 ± 4.80 years for the NH participants, and overall were less agile and so less able to turn toward the ground, particularly as the seating was low and they were essentially sitting over speaker one. The less than ideal seating also meant participants legs were more likely to cover the lower two speakers which may have interfered with the stimuli.

On closer examination of the results, there were no clear similarities between the participants who made the most large (> 90°) errors of selection which generally equate to the front/back or up/down errors discussed in other literature (Best et al., 2005; Carlile et al., 1997; Carlile et al., 1999; Gilkey & Anderson, 1995; Langendijk & Bronkhorst, 2002; Makous & Middlebrooks, 1989; Middlebrooks, 1992). In Experiment 2, of the HL individuals that made the large errors of selection more than 15% of the time, four of the six were female. They had a variety of hearing losses ranging from hearing within normal limits (not exceeding 20 dB HL) at 8 kHz sloping to a moderate hearing loss at frequencies between 10 to 12.5 kHz (HL 20) to hearing within normal limits at 4 kHz sloping to a severe hearing loss at 11.2 kHz with no registered hearing at 14 kHz (5). Of the HL participants (from the group of six that made large errors more than 15% of the time) two consistently made large errors regardless of stimuli and frequency content, (HL 20 and 22). Both of these participants were male, one with one of the most severe hearing losses (HL 22) and the other (HL 20) with one of the milder hearing losses. Of the NH group, six participants also made large errors more than 15% of the time. Three of these participants (NH 29, 42 and 43) made large errors with all stimuli. As both hearing groups were biased toward females (16 females : 7 males), and therefore not truly representative of a balanced population, no conclusions can be made regarding the influence of gender and hearing loss status on the proportion of large errors of selection.

In Experiment 4 there was only one participant in each hearing group who made large errors (> 90°) of selection more than 15% of the time. Therefore, for this experiment it was decided to compare participants who made the large errors more than 8% of the time. Of the five HL participants who met this criterion, one of the five was male and four female. There was no obvious trend found with respect to severity of hearing loss and proportion of large errors of selection. There were also five NH participants who made large errors greater than 8 % of the time; two being male and three female. There were three participants (HL 11, HL 35, NH 35) who made greater than 8% of errors for at least two stimulus conditions. One female participant (NH 27) made a large number of errors in both

Experiment 2 and 4. It is interesting that while there is no evidence of a gender difference for this experiment, it has been noted by Otte et al. (2013) that ear pinna size can influence localization ability in elevation, and females in general have a small pinna size than males. Therefore it was speculated that females may need more high frequency information than males for accurate localization in elevation, although clearly given our small subject numbers and larger percentage of females in the group, no conclusions can be drawn on this issue from the present data

It had been anticipated that overall that there would be more large errors of selection in the 8 kHz filtered condition compared to the 16 kHz low-pass filtered condition. This was the case when comparing the overall means between 8 kHz and 16 kHz for all stimulus conditions (strong speech, weak speech) for both Experiment 2 and Experiment 4 with the exception of the NH group for noise. This trend suggests that the extra frequency information in the 16 kHz filtered stimuli may provide important cues for localization. However, it can be seen from the confusion matrices for Experiment 2 (refer to Figures 24 and 25) for a number of participants (HL 3, 21, 22 and NH 26, 34, 35) that the majority of the front/back errors are made in the 8 kHz and 16 kHz noise conditions but none are made in any of the speech conditions. This indicates that for Experiment 2 the stimulus difference is of more importance in reducing large errors of selection than a broader frequency range.

The study by Best et al. (2005) found the lowest percentage of cone of confusion (COC) errors (which equates to the large errors of selection in the current experiment) for the broadband noise condition with both speech conditions having a higher amount of COC errors. Of the two speech conditions Best et al. (2005) found that the broadband speech (equivalent to 16 kHz speech condition) condition had less COC errors than low pass speech (equivalent to 8 kHz speech condition). A similar trend for speech stimuli was found in the current experiment with the 16 kHz stimuli having a lower proportion of large errors of selection for both groups in all stimuli conditions except for NH participants for the noise condition. This is in agreement with Best et al.'s (2005) suggestion that information in the frequencies between 8 and 16 kHz can contribute to speech localization ability.

This trend has also been found in previous research such as Langendijk and Bronkhorst (2002), who examined the influence of spectral cues varying in bandwidth and centre frequency on localization. These authors found that while there was variation amongst their 8 listeners, a greater number of back/front errors were made with the removal of cues in the 8 to 16 kHz octave condition in comparison to the 4 - 8, and 5.7 – 11.3 kHz conditions.

4.6 Limitations of the Study

4.6.1 Participants

Limitations of the study need to be considered in evaluating the results. Firstly, the sample size of 23 participants in each hearing group may have resulted in low statistical power, and therefore care needs to be taken when generalising the results to a larger population. However, it is noted that many localization studies use small sample sizes, ranging from three to nine participants (Best et al., 2005; Carlile et al., 1999; Gilkey & Anderson, 1995; King & Oldfield, 1997; Langendijk & Bronkhurst, 2002; Makous & Middleton, 1989; Middlebrooks, 1992; Wightman & Kistler, 1992). In addition, the participants were sourced from a select group of people accessible to the researcher such as University of Canterbury students and staff, people recruited from the Speech and Language clinic, and others by word of mouth. The participants therefore did not reflect the greater ethnic and socioeconomic makeup of the wider community in Christchurch.

As noted above, in both groups, there was a bias towards females; sixteen female and seven males in each group. While the groups were equivalent in gender it still may have had an impact on results, particularly as males generally have larger pinnas which has been found to compensate for minor to moderate hearing losses in some localization tasks (Otte et al., 2013). The mean age of the hearing loss group (53.7 ± 9.10 years) was also a lot older than the normal hearing group (24.65 ± 4.80 years) which may have introduced an age effect. Dobreva et al. (2013), suggested in their study on the effect of aging on localization that differences in accuracy may be as a result of decreased central processing, in addition to peripheral hearing loss.

In addition to central processing issues it was noted that several of the older participants were less agile than younger participants, which may have had an impact on their ability to localize. After hearing the stimuli, participants were required to turn and call out the number of the speaker they perceived the noise or speech to come from. For experiments 2 and 4, participants were side on to the speaker arrangement. In these seating positions some of the older participants found it a lot more difficult to turn and look at the speakers and so this may have had an impact on the speaker they chose. Although it is noted that more of the normal hearing participants made front-back errors in this speaker arrangement, which contradicts the effect expected if agility is inhibiting localization. In Experiment 3 when the speakers were in the vertical position a greater pattern of error was found in the lower positions for the hearing loss participants. Interestingly, different participants had different methods of mentally processing where they perceived the location of the stimuli, some turning after hearing the stimulus but others closing their eyes and visualizing mentally where they thought the stimuli was being presented rather than turning.

Initially the researcher had intended to recruit listeners who had hearing within normal limits (thresholds of 20 dB HL and better up to 4 kHz) in an attempt to isolate an effect of the extended high frequencies hearing loss. However, it soon become apparent that it was going to be difficult to find enough participants with the ‘ideal’ hearing loss of a moderate to severe hearing loss from 6 kHz to 16 kHz and as a result the audiograms were quite variable. The researcher also sought participants with a sensorineural hearing loss and while it was presumed that all participants had a hearing loss of this nature, due to their self-reporting of no known middle ear dysfunction, it would have been beneficial to have this confirmed. This could have been conducted via tympanometry; however this was not possible due to limited availability of immittance equipment.

None of the participants had been involved in localization experiments in the past. However, many of the normal hearing participants were first and second year students enrolled in the Audiology Masters programme at the University of Canterbury and as a consequence had been taught some theory about localization processes. It is however, considered unlikely that this knowledge would have had been an advantage for the task.

4.6.2 Equipment

The experiment had to be produced within a certain budget and as a result there were limitations to the set up and the number of sound sources. This included using four virtual speakers, in addition to a dummy speaker, which did not emit any sound; however it would have been best to use actual speakers. Ideally it would be an advantage to use a large globe arrangement such as the experimental equipment of Gilkey and Anderson, (1995) who had access to a large geodesic sphere which had 224 speaker locations. In the current experiment the speakers were also placed 15° apart, except where there was a dummy speaker and a corresponding 30° gap. Closer speakers may have provided a more sensitive measure of localization which could have identified a greater number of significant differences between the two groups. Previous research by Makous and Middlebrooks (1989) found their participants had spatial acuity of 2° for frontal broadband stimuli and 3.5° for frontal vertical locations.

In more recent studies there is some variability in distance between locations. Dobreva et al. (2011) used speakers positioned 10° apart as did King and Oldfield (1997). Otte et al. (2013) used a spatial resolution of 2.5° and Gilkey and Anderson (1995) used speakers 8° to 15° apart, whereas Yost et al. (2013) and Brungart and Simpson, (2009) used 15° increments. Equipment issues are less of a problem with virtual stimuli; for example Best et al. (2005) used 76 stimulus locations and Langendijk and Bronkorst (2002) used 23 positions in the right hemisphere. The arc in the present study was constructed using plywood and a modified engine hoist as the point of rotation between the planes. While all care was taken during construction it would have not been as accurate as fixing the speakers in precisely the correct location as a bespoke engineered device.

The radius of the arc was also limited by the height of the room which was less than 2 m and therefore the researcher felt the distance between the participants head and the speakers was quite small. However, in free field experiments such as Dobreva et al. (2011)

there were comparable restrictions in room height of 2.7m, while Yost et al. (2013) used an experimental radius of 1.67m.

4.6.3 Stimuli

The speech stimuli used was compiled from a list of words that had a substantial high frequency content above 8 kHz, and was spoken by a female speaker. As previously stated, the speech was deliberately weighted this way to maximise the likelihood that any significant difference in localization ability due to the high frequency content be detected. However, it could be argued that it was not a true representation of speech, and it could be more balanced with speech with greater low-frequency content. In future studies it would also be of interest to compare the localization abilities with stimuli featuring speakers of different genders, ages and languages.

One potentially significant issue was that there was only one presentation per speaker in each experiment for the weak speech stimuli. This was initially done this way as when it is added to the number of strong speech stimuli per speaker it totalled four, corresponding to the total presentations of noise. Most of the localization studies use at least 3 presentations or more per location (Best et al., 2005; Langendijk & Bronkhurst, 2002; Makous & Middlebrooks, 1989; Middlebrooks, 1992; Otte et al., 2013; Yost et al., 2013; Zhang & Hartmann, 2009). However, due to the limited time frame that the participants were able to concentrate for, and the number of experimental stimuli and arrangements, it was decided that compromises needed to be made so as not to have an unreasonable number of total presentations. As a consequence, the weak speech stimuli results have less validity than the other stimuli.

4.6.4 Procedure

As mentioned previously, across studies there is quite a large variation in procedure. It is felt that method of communicating response, training and feedback are particularly worth discussing further as they have relevance to the current study. In the current study, a verbal response was used. However, it has been found that non-verbal responses are closer to the perception of the stimuli than using a verbal response method (Mason, Ford, Rumsey & De Bruyn, 2001). Initially it had been intended for the participant to point with their arm first and then turn and call out the number of the speaker. However due to the arc being small and initially the fishing line for orientation being in the way, this technique was not used.

A further disadvantage of turning is that further error may occur due to the motor component of the response and a slower movement may also show greater memory related errors (Carlie, et al., 1997). This may have occurred in particular with the older participants where it was noted that some of the less agile participants struggled to turn their heads for stimulus that was directly behind and above them, and took longer to turn and call out the perceived location. The 67 year old participant mentioned at the end of the study that she may have to go and visit her chiropractor due to the turning activity.

4.7 Directions for Further Research

One of the next steps in the experiment would be to introduce background noise to see if this made any difference to localization ability. It was felt that this would provide a more real world situation as most listeners need to localize in an environment where there is background noise. In the planning stages this had been the intent, however due to time constraints this was not possible. The localization activity took approximately one and a quarter hours and participants were reasonably tired by the end of the activity. To attempt to bring participants back again was considered unrealistic, especially as the majority had undergone the audiogram and localization tasks on two separate occasions.

In the future it would also be interesting to determine which frequency bands have the most effect on localization ability and how much hearing loss is required in particular frequency bands. In the current study, the audiograms were variable in terms of hearing loss at different frequencies; for example at 10 kHz HL participants' audiograms ranged from 20 dB HL to 50 dB HL. As a consequence of this variation analysis became difficult. In addition, it would be interesting to determine how the sound intensity of the stimuli had an impact on localization error with the two groups of participants as was undertaken by Best et al. (2005) with the frequencies 8 kHz and above. By reducing the stimulus level a significant difference in localization may have been found between the two groups.

It has also been found that training and feedback has an effect on localization performance (Majadak et al., 2010). As a consequence, training or orientation often takes place in localization studies to increase reliability (Carlile et al., 1999; Dobreva, 2013; Makous & Middlebrooks, 1990), or those participants previously experienced in localization tasks are utilised (Langendijk & Bronkhurst, 2002). In their study focusing on the effect of training using three dimensional space, Majdak et al. (2010) found that a training effect was found after visual feedback until a certain accuracy of localization was obtained. In the current study no feedback was given, and there were only five practise presentations of speech and five for noise for each experimental arrangement. However, it was noted that several participants made the comment that if they were given verbal feedback initially they felt they could have done much better. Training was out of the scope of this study; however it would be interesting in the future to see whether training made an impact on localization accuracy and performance within and between participants especially in Experiments 2 and 3 where more variability of localization ability was found.

4.8 Conclusion

The current study investigated whether there were differences in localization ability between normal hearing participants and participants with a hearing loss mainly limited to the extended high frequencies. Additionally, whether noise and speech stimuli band pass filtered at two different high-frequency cut offs made any difference to localization performance. The results showed that there were no overall significant main effect differences in localization ability between the two groups of participants for the four experiments (two in the horizontal plane and two in the vertical plane). However, within experiments significant localization differences were found between the two groups. For Experiments 3 and 4, the HL participants localized more poorly for lower speakers that the NH participants; although it was queried whether this was due to external factors. In Experiment 4 the NH group localized significantly better in the two speech conditions than the HL group. The results further showed that overall, participants benefitted from having a wider filter band pass of 16 kHz compared to 8 kHz, and speech over noise; however, this advantage was only found to be significant in certain locations. Future research could extend the study and look at more real world environments such as using background noise to determine whether this had a different impact on localization ability between the two groups.

References

Abel, S.M., & Banerjee, P.J. (1996). Accuracy versus choice response time in sound localization. *Applied Acoustics, 49*(4), 405-417.

Abel, S.M., Giguère, C., Consoli, A., & Papsin, B.C. (2000). The effect of aging on horizontal plane sound localization. *Journal of the Acoustical Society of America, 108*(2), 743-752.

Abouchacra, K.S., Emmanuel, D.C., Blood, I.M., & Tomasz, R. (1998). Spatial perception of speech in various signal to noise ratios. *Ear and Hearing, 19*(4), 298-309.

Ahmed, H. O., Dennis, J. H., Badran, O., Ismail, M., Ballal, S. G., Ashoor, A., & Jerwood, D. (2001). High-frequency (10-18 kHz) hearing thresholds: Reliability, and effects of age and occupational noise exposure. *Occupational Medicine: Oxford, 51*(4), 245-258. doi: 10.1093/occmed/51.4.245

Akeroyd, M.A., & Guy, F.H. (2011). The effect of hearing impairment on localization dominance for single word stimuli. *Journal of the Acoustical. Society.of America,. 130*(1), 312-323.

Angeli, S. I., Yan, D., Telischi, F., Balkny, T. J., Ouyang, X. M., Du, L.L., Eshraghi, A., Goodwin, L., Liu, X. (2005). Etiologic diagnosis of sensorineural hearing loss in adults. *Otolaryngology - Head and Neck Surgery, 132*(6), 890-895.

Arora, R., Thakur, J., Azad, R., Mohindroo, N., Sharma, D., & Seam, R. (2009). Cisplatin-based chemotherapy: Add high-frequency audiometry in the regimen. *Indian Journal of Cancer, 46*(4), 311-317. doi: 10.4103/0019-509X.55551

Ashihara, K. (2007). Hearing thresholds for pure tones above 16 kHz. *Journal of the Acoustical Society of America, 122*(3), EL52-EL57.

Ashmore, J. (2008). Cochlear outer hair cell motility. *Physiological Review,* (88), 173-210.

Balakrishnan, U., & Freyman, R.L. (2008). Speech detection in spatial and nonspatial speech maskers. *Journal of the Acoustical Society of America, 123*(5), 2680-2691.

Balatsouras, D. G., Homsioglou, E., & Danielidis, V. (2005). Extended high-frequency audiometry in patients with acoustic trauma. *Clinical Otolaryngology, 30*(3), 249-254.

Bernstein, L.R., & Trahiotis, C. (2002). Enhancing sensitivity to interaural delays at high frequencies by using "transposed stimuli." *Journal of the Acoustical Society of America, 112.* 1026-1036.

Best, V., Carlile, S., Jin, C., & Van Schaik, A. (2005). The role of high frequencies in speech localization. *Journal of the Acoustical Society of America,* 353-363. doi: 10.1121/1.1926107

Blauert, J. (1997). *The psychophysics of human sound localization*. Cambridge, England: MIT Press.

Brungart, D., & Simpson, B.D. (2009). Effects of bandwidth on auditory localization with a noise masker. *Journal of the Acoustical Society of America, 126*(6), 3199-3208. doi: 10.1121/1-3243309

Cahart, R., & Jerger, J.F. (1959). Preferred Methods for Clinical Determination of Pure-Tone Thresholds. *J. Speech Hear. Res., 24,* 330-345.

Carlile, S., Leong, P., & Hyams, S. (1997). The nature and distribution of errors in sound localization by human listeners. *Hearing Research, 114*(1)*,* 179-196.

Carlile, S., Delaney, S.E., & Corderoy, A. (1999). The localization of spectrally restricted sounds by human listeners. *Hearing Research, 128*(1-2), 175-189.

doi: http://dx.doi.org/10.1016/S0378-5955(98)00205-6

Dobreva, M.S., O'Neill, W.E., & Paige, G.D. (2011). Influence of aging on human sound localization. *Journal of Neurophysiology, 105*(5), 2471-2486. doi: 10.1152/jn.00951.2010

Dreschler, W. A., Vanderhulst, R., Tange, R. A., & Urbanus, N. A. M. (1989). Role of high frequency audiometry in the early detection of ototoxicity 2. Clinical aspects. *Audiology, 28*(4), 211-220.

Dubno, J.R., Ahlstrom, J.B., & Horwitz, A.R. (2002). Spectral contributions to the benefit from spatial separation of speech and noise. *Journal of Speech, Language and Hearing Research. 45*(6), 1297-1310.

Egan, J.P. (1947). Articulation testing methods: The quantitative evaluation of the intelligibility of speech. Dissertation submitted to Harvard University, Massachusetts, United States of America.

Encyclopaedia Britannica. (1997). *Basilar membrane : Analysis of sound frequencies.* Retrieved from http:www.britannica.com/EBchecked/media/537/The-analysis-of-sound-frequencies-by-the-basilar-membrane/topicid=175622

Frank, T. (2001). High-frequency (8 to 16 kHz) reference thresholds and intrasubject threshold variability relative to ototoxicity criteria using a Sennheiser HDA 200 earphone. *Ear and Hearing, 22*(2), 161-168.

Fulop, S.A. (2011). *Speech Spectrum Analysis.* USA: Springer.

Gabriel, K.J., Koehnke, J., & Colburn, H.S. (1992). Frequency dependence of binaural performance in listeners with impaired binaural hearing. *Journal of the Acoustical Society of America, 91*(1), 336-347.

Gilkey, R., & Anderson, T. (1995). The accuracy of absolute localization judgements for speech stimulus. *Journal of Vestibular Research: Equilibrium and Orientation, 5*(6), 487-497.

Hallmo, P., Sundby, A., & Mair, I. W. (1994). Extended high-frequency audiometry. Air- and bone-conduction thresholds, age and gender variations. *Scandanavian Audiology, 23*(3), 165-170.

Jin, C., Corderoy, A., Carlile, S., & Van Schaik, A. (2004). Contrasting monaural and interaural spectral cues for human sound localization. *Journal of the Acoustical Society of America, 115*(6), 3124-3141.

Karlsen, B. L. (1999). *Spatial localization of speech segments*. Ph. D. Dissertation submitted to The Faculty of Engineering and Science, Aalbourg University, Denmark.

Kim, D. K., Park, S. N., Kim, H. M., Son, H. R., Kim, N. G., Park, K. H., & Yeo, S. W. (2011). Prevalence and significance of high-frequency hearing loss in subjectively normal-hearing patients with tinnitus. *Annals of Otology, Rhinology and Laryngology, 120*(8), 523-528.

King, R.B., & Oldfield, S.R. (1997). The impact of signal bandwidth on auditory localization: Implications for the design of three-dimensional audio displays. *Human Factors, 39*(2), 287-295. doi: 10.1518/001872097778543895

Kopco, N., Best, V., & Carlile, S. (2010). Speech localization in a multitaker mixture. *Journal of the Acoustical Society of America,. 127* (3), 1450-1457.

Langendijk, E.H.A., & Bronkhorst, A.W. (2002). Contribution of spectral cues to human sound localization. *Journal of the Acoustical Society of America, 112*(4), 1583-1596. doi: 10.1121/1.1501901

Langendijk, E.H.A., Kistler, D.J., & Wightman, F.L. (2001). Sound localization in the presence of one or two distractors. *Journal of the Acoustical Society of America, 109*(5,Pt 1), 2123-2134. doi: 10.1121/1.1356025

Lee, J., Dhar, S., Abel, R., Banakis, R., Grolley, E., Lee, J., . . . Siegel, J. (2012). Behavioral hearing thresholds between 0.125 and 20 kHz using depth-compensated ear simulator calibration. *Ear and Hearing, 33*(3), 315-329. doi: 10.1097/AUD.0b013e31823d7917

Lewis, W. H. (Eds.). (2000). *Gray's Anatomy of the Human Body.* (20th ed.) New York: Bartleby.com

Macpherson, E.A., & Sabin, A.T. (2013). Vertical-plane sound localization with distorted spectral cues. *Hearing Research, 306*, 76-92. doi: 10.1016/j.heares.2013.09.007

Makous, J.C., & Middlebrooks, J.C. (1989). Two-dimensional sound localization by human listeners. *Journal of the Acoustical Society of America, 87(*5), 2188-2200.

Mason, R., Ford, N., Rumsey, F., & De Bruyn, B. (2001). Verbal and non-verbal elicitation techniques in the subjective assessment of spatial sound reproduction. *Journal of the Audio Engineering Society, 49*(5)*,* 336-384.

Mehrparvar, A. H., Mirmohammadi, S. J., Ghoreyshi, A., Mollasadeghi, A., & Loukzadeh, Z. (2011). High-frequency audiometry: A means for early diagnosis of noise-induced hearing loss. *Noise and Health, 13*(55), 402-406. doi: 10.4103/1463-1741.90295

Middlebrooks, J. C. (1992) Narrow-band sound localization related to external ear acoustics. *Journal of the Acoustical Society of America, 92*(5), 2607-2624. doi: 10.1121/1.404400

Middlebrooks, J.C., & Green, D.M. (1990). Directional dependence of interaural envelope delays. *Journal of the Acoustical Society of America, 87*(3), 2149-2162.

Monson, B.B., Lotto, A.J., & Ternström, S. (2011). Detection of high-frequency energy changes in sustained vowels produced by singers. *Journal of the Acoustical Society of America, 129(*4*),* 2263-2268. doi: 10.1121/1.3557033

Monson, B. B., Hunter, E. J., & Story, B. H. (2012). Horizontal directivity of low and high-frequency energy in speech and singing. *Journal of the Acoustical Society of America, 132*(1), 433-441. doi: 10.1121/1.4725963

Monson, B. B., Lotto, A. J., & Story, B. H. (2012). Analysis of high-frequency energy in long-term average spectra of singing, speech, and voiceless fricatives. *Journal of the Acoustical Society of America, 132*(3), 1754-1764.

Moore, B,C., Shailer, M.J., & Schooneveldt, G.P. (1992). Temporal modulation transfer functions for band-limited noise in subjects with cochlear hearing loss. *British Journal of Audiology, 26*(4), 229-237.

Moore, B. C. (2007). *Cochlear hearing loss: Physiological, psychological and technical issues* (2nd ed.). England: John Wiley & Sons Ltd.

Moore, B. C. J. (1985). Frequency selectivity and temporal resolution in normal and hearing-impaired listeners. *British Journal of Audiology, 19*(3), 189-201. doi:y10.3109/03005368509078973

Moore, B. C. J., Fullgrabe, C., & Stone, M. A. (2010). Effect of spatial separation, extended bandwidth, and compression speed on intelligibility in a competing speech task. *Journal of the Acoustical Society of America, 128*(1), 360-371.

Moore, B. C. J., Stone, M. A., Fullgrabe. C., Glasberg, B. R., & Puria, S. (2008). Spectro-temporal characteristics of speech at high frequencies, and the potential for restoration of audibility to people with mild-to-moderate hearing loss. *Ear and Hearing, 29*(6), 907-922. doi: 10.1097/AUD.0b013e31818246f6

Moore, B. C. J., & Tan, C-T. (2003). Perceived naturalness of spectrally distorted speech and music. *Journal of the Acoustical Society of America, 114*(1), 408-419.

Musiek, F.E., & Baran, J.A. (2007). *The auditory system: Anatomy, physiology, and clinical correlates.* Boston, USA: Pearson.

Noble, W., Byrne, D., & Lepage, B. (1994). Effects on sound localization of configuration and type of hearing impairment. *Journal of the Acoustical Society of America, 95*(2), 992-1005. doi:http://dx.doi.org/10.1121/1.408404

Otte, R.J., Martijn, J.H., Agterberg, M.J.H., Van Wanrooij, M.M., Snik, A.F.M., & Van Opstal, A.J. (2013). Age-related hearing loss and ear morphology affect vertical but not horizontal sound-localization performance. *Jaro-Journal of the Association for Research in Otolaryngology, 14*(2), 261-273. doi: 10.1007/s10162-012-0367-7

Parmet, S. (2007). Adult hearing loss. *The Journal of the American Medical Association, 298*(1), 130.

Perrett, S., & Noble, W. (1997). The contribution of head motion cues to localization of low pass noise. *Perception and Psychophysics, 59*(7), 1018-1026. doi: 10.3758/bf03205517

Pickles, J.O. (1988). *An introduction to the physiology of hearing.* London: Academic Press.

Starkey Research, S. (2008). Binaural presentation. Retrieved from http://www.starkeyresearch.com/pdfs/binaural presentation.pp.

Ryan, A.F. (2000). Protection of auditory receptors and neurons: Evidence for interactive damage. *Proceedings of the National Academy of Sciences of the United States of America, 97*(13), 6939-6940. doi: 10.1073/pnas.97.13.6939

Sakamoto, M., Sugasawa, M., Kaga, K., & Kamio, T. (1998). Average thresholds in the 8 to 20 kHz range as a function of age. *Scandanavian Audiology, 27*(3), 189-192.

Schmuziger, N., Probst, R., & Smurzynski, J. (2004). Test-retest reliability of pure-tone thresholds from 0.5 to 16 kHz using Sennheiser HDA 200 and etymotic research ER-2 earphones. *Ear and Hearing, 25*(2), 127-132.

Schmuziger, N., Brechbuehl, M., & Probst, R. (2007). Acoustic measures of low-frequency noise in extended high-frequency audiometry. *Journal of the Acoustical Society of America, 121*(3), EL 120 - EL 124 doi: 10.1121/1.2437848

Shim, H. J., Kim, S. K., Park, C. H., Lee, S. H., Yoon, S. W., Ki, A. R., . . . Yeo, S. G. (2009). Hearing abilities at ultra-high frequency in patients with tinnitus. *Clinical and Experimental Otorhinolaryngology, 2*(4), 169-174. doi: 10.3342/ceo.2009.2.4.169

Slepecky, N.B.(1996). Structure of the mammalian cochlea. In P. Dallos, A. Popper, & R. Fay (Eds.) *The Cochlea (Springer handbook of Auditory Research, Vol. 8),* pp. 44-129. New York: Springer.

Smith-Olinde, l., Koehnke, J., & Besing, J. (1998). Effects of sensorineural hearing loss on interaural discrimination and virtual localization. *Journal of the Acoustical Society of America, 103(*4), 2084-2099.

Smith, D. W., Moody, D.B., Stebbins, W.C., & Norat, M.B. (1987). Effects of outer hair cell loss on the frequency selectivity of the patas monkey auditory system. *Hearing Research, 29*(2), 125-138.

Somma, G., Coppeta, L., Magrini, A., Parrella, M., Cappelletti, M. C., Gardi, S., . . . Bergamaschi, A. (2007). Extended high frequency audiometry in the prevention of noise-induced hearing loss. *Giornale Italiano di Medicina del Lavoro ed Ergomia, 29*(3 Suppl), 258-260.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2001). Effect of stimulus bandwidth on the perception of /s / in normal and hearing-impaired children and adults. *Journal of the Acoustical Society of America, 110*(4), 2183-2190.

Taylor, B., & H.G. Mueller. (2011). *Fitting and dispensing hearing aids.* San Diego: Plural Publishing Inc.

Venema, T. H. (2006). *Compression for clinicians* (2nd ed.). Delmar, USA: Cengage Learning.

Wang, Y., Yang, B., Li, Y., Hou, L., Hu, Y., & Han, Y. (2000). Application of extended high frequency audiometry in the early diagnosis of noise-induced hearing loss. *Zhonghua Er Bi Yan Hou Ke Za Zhi, 35*(1), 26-28.

Weissenstein, A., Deuster, D., Knief, A., Zehnhoff-Dinnesen, A. A., & Schmidt, C. M. (2012). Progressive hearing loss after completion of cisplatin chemotherapy is common and more pronounced in children without spontaneous otoacoustic emissions before chemotherapy. *International Journal of Pediatric Otorhinolaryngology, 76*(1), 131-136. doi: 10.1016/j.ijporl.2011.10.020

Wightman, F.L., & Kistler, D. J. (1992). The dominant role of low-frequency interaural time differences in sound localization. *Journal of the Acoustical Society of America, 91*(3), 1649-1661.

Wiley, T. L., Cruickshanks, K. J., Nondahl, D. M., Tweed, T. S., Klein, R., & Klein, B. E. K. (1998). Aging and high-frequency hearing sensitivity. *Journal of Speech, Language and Hearing Research, 41*(5), 1061-1072.

Yates, G. K., Johnstone, B. M., Patuzzi, R. B., & Robertson, D. (1992). Mechanical preprocessing in the mammalian cochlea. *Trends in Neurosciences, 15*(2), 57-61. doi: http://dx.doi.org/10.1016/0166-2236(92)90027-6

Yildirim, G., Berkiten, G., Kuzdere, M., & Ugras, H. (2010). High frequency audiometry in patients presenting with tinnitus. *Journal of International Advanced Otology, 6*(3), 401-407.

Yost, W. A., Loiselle, L., Dorman, M., Burns, J., & Brown, C. A. (2013). Sound source localization of filtered noises by listeners with normal hearing: A statistical analysis. *Journal of the Acoustical Society of America, 133*(5), 2876-2882. doi: 10.1121/1.4799803

Zhang, P.X., & Hartmann, W.M. (2010). On the ability of human listeners to distinguish between front and back. *Hearing Research,* 260(1-2), 30-46. doi: 10.1016/j.heares.2009.11.001

Appendices

Appendix 1. Localization Brochure for Participants

Who can participate?

We are looking for people who likely have an extended high frequency hearing loss.

People who fit this category may already have a high frequency hearing loss that they know about, or they may be unaware of it. In some cases they may have had ear surgery, cancer treatment or exposure to excessive noise.

We are also looking for people with normal hearing.

You will receive a free hearing test and participate in a localization experiment at the University of Canterbury. This involves listening to sounds and pointing to their perceived location.

It will take approximately 2 hours. The first visit involves 1/2 an hour for a hearing test and the second 1 and 1/2 hours for the experiment.

Please make contact :

Dept. of Communication Disorders

Sarah Gray

Masters of Audiology student

Ph: 0276505055

Email: seg60 @uclive.ac.nz

Dr. Greg O' Beirne

Audiology Lecturer

Ph: + 64 3 364 2987 ext. 7085

Email: gregory.obeirne@canterbury.ac.nz

Melissa Babbage

Audiology Lecturer/ Audiologist

Email: melissa.babbage@pg.canterbury.ac.nz

University of Canterbury

UC UNIVERSITY OF CANTERBURY *Te Whare Wānanga o Waitaha* CHRISTCHURCH NEW ZEALAND

The Effects of Extended High Frequency Hearing Loss on the Ability to Localize Sound

Appendix 2. Participant Consent Form

Study assessing localization ability of people with an extended high frequency hearing loss

Participant Consent Form

An interpreter is not readily available, if you would like an interpreter we will endeavour to find one:

English	I wish to have an interpreter.	Yes	No
Maori	E hiahia ana ahau ki tetahi kaiwhakamaori/kaiwhaka pakeha korero.	Ae	Kao
Cook Island	Ka inangaro au i tetai tangata uri reo.	Ae	Kare
Fijian	Au gadreva me dua e vakadewa vosa vei au	Io	Sega
Niuean	Fia manako au ke fakaaoga e taha tagata fakahokohoko kupu.	E	Nakai
Samoan	Ou te mana'o ia i ai se fa'amatala upu.	Ioe	Leai
Tokelaun	Ko au e fofou ki he tino ke fakaliliu te gagana Peletania ki na gagana o na motu o te Pahefika	Ioe	Leai
Tongan	Oku ou fiema'u ha fakatonulea.	Io	Ikai

Please read and tick the appropriate box:

I have read and understood the project information sheet "Study assessing localization ability of people with an extended high frequency hearing loss" ☐ ☐

◦ I have had the opportunity to ask questions about the study, and am satisfied with the answers I have been given.

◦ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time. ☐ ☐

◦ I understand that taking part in this study is confidential and no material that could identify me will be used in any reports of this study. ☐ ☐

◦ I have had time to consider whether to take part in this study. ☐ ☐

I, ____[insert your full name]

Hereby consent to taking part in this study. I understand that this will involve having a typical and extended high frequency audiogram and if suitable further localization testing.

Signed:___________ Date (day/month/year): ___/___/___

Project explained by:________________ Signed:________________________

At the end of the study I would like a copy of the results to be sent to me Yes ☐ No ☐

Thank you, for your assistance.

Sarah Gray

Masters of Audiology Student

Dr Greg O'Beirne

Lecturer in Audiology

Melissa Babbage

Lecturer in Audiology

Appendix 3. List of words

#	Percent	8 kHz - 16 kHz	Filename	Unfiltered	0 - 300 Hz	300 Hz - 8 kHz
1	0%	-35.77	female_list01_such.wav	-22.45	-40.85	-22.67
2	0%	-36.05	female_list04_hiss.wav	-32.98	-38.1	-36.44
3	1%	-36.97	female_list04_slap.wav	-28.75	-40.31	-29.49
4	1%	-37.34	female_list01_pants.wav	-30.22	-35.86	-31.39
5	1%	-37.36	female_list07_sin.wav	-32.44	-29.99	-35.6
6	1%	-37.4	female_list04_strap.wav	-26.78	-43.81	-27.18
7	2%	-37.5	female_list04_race.wav	-31.37	-36.59	-32.78
8	2%	-37.63	female_list01_slip.wav	-32.3	-35.54	-34.29
9	2%	-37.84	female_list01_fuss.wav	-28.54	-43.25	-29.1
10	2%	-37.9	female_list04_scab.wav	-26.52	-36.65	-26.89
11	2%	-38.33	female_list01_pest.wav	-32.75	-39.5	-34.35
12	3%	-38.54	female_list01_strife.wav	-29.13	-39.15	-29.72
13	3%	-38.58	female_list03_nest.wav	-32.43	-30.84	-34.69
14	3%	-38.65	female_list04_sketch.wav	-30.91	-42.78	-31.78
15	3%	-38.67	female_list02_moose.wav	-32.64	-27.1	-39.03
16	4%	-38.73	female_list07_south.wav	-25.08	-39.76	-25.29
17	4%	-38.75	female_list09_ice.wav	-26.91	-38.7	-27.24
18	4%	-38.82	female_list03_sit.wav	-35.64	-40.9	-38.98
19	4%	-38.85	female_list02_suck.wav	-29.19	-42.51	-29.72
20	5%	-38.89	female_list10_scrub.wav	-28.41	-36.95	-28.89
21	5%	-39.17	female_list06_best.wav	-26.04	-35.67	-26.31
22	5%	-39.18	female_list04_bus.wav	-23.19	-41.12	-23.31
23	5%	-39.43	female_list04_test.wav	-30.87	-39.98	-31.6
24	5%	-39.51	female_list04_sour.wav	-26.52	-37.84	-26.78
25	6%	-39.59	female_list02_niece.wav	-31.6	-29.62	-33.98
26	6%	-39.6	female_list07_siege.wav	-34.92	-31.65	-39.26
27	6%	-39.65	female_list02_scythe.wav	-25.55	-35.93	-25.78
28	6%	-39.76	female_list07_sniff.wav	-32.41	-34.14	-33.93
29	7%	-39.87	female_list07_sledge.wav	-28.56	-35.34	-29.03
30	7%	-40.1	female_list07_dose.wav	-31.84	-35.14	-32.91
31	7%	-40.23	female_list08_deuce.wav	-33.29	-29.07	-37.7
32	7%	-40.36	female_list05_solve.wav	-29.93	-37.64	-30.42
33	7%	-40.39	female_list07_gasp.wav	-26.16	-38.4	-26.36
34	8%	-40.51	female_list08_ask.wav	-24.43	-39.12	-24.55
35	8%	-40.51	female_list09_grace.wav	-30.23	-35.88	-30.85
36	8%	-40.53	female_list05_sick.wav	-35.27	-42.06	-37.01
37	8%	-40.59	female_list09_sip.wav	-36.71	-42.08	-39.28
38	9%	-40.6	female_list04_beast.wav	-33.15	-29.39	-36.93
39	9%	-40.62	female_list04_sage.wav	-32.23	-36.58	-33.16
40	9%	-40.7	female_list02_sludge.wav	-26.62	-35.6	-26.87
41	9%	-40.76	female_list02_else.wav	-29.15	-40.32	-29.5
42	10%	-40.79	female_list06_thus.wav	-29.55	-37.24	-29.96

43	10%	-40.85	female_list06_pus.wav	-31.95	-40.64	-32.63
44	10%	-40.9	female_list09_boost.wav	-32.11	-28.11	-35.8
45	10%	-40.92	female_list03_size.wav	-29.59	-36.98	-30.01
46	10%	-40.96	female_list10_staff.wav	-27.96	-39.29	-28.23
47	11%	-40.97	female_list02_vast.wav	-26.24	-36.92	-26.44
48	11%	-41.07	female_list09_chest.wav	-29.29	-39.65	-29.65
49	11%	-41.08	female_list04_course.wav	-29.9	-39.61	-30.31
50	11%	-41.12	female_list02_snuff.wav	-28.99	-38.69	-29.36
51	12%	-41.12	female_list02_start.wav	-27.59	-40.17	-27.83
52	12%	-41.15	female_list10_chance.wav	-27.93	-37.32	-28.22
53	12%	-41.16	female_list09_chess.wav	-29.99	-42.35	-30.39
54	12%	-41.18	female_list01_box.wav	-25.31	-39.03	-25.45
55	12%	-41.22	female_list02_bounce.wav	-25.17	-37.29	-25.3
56	13%	-41.22	female_list09_noose.wav	-32.45	-25.54	-39.73
57	13%	-41.27	female_list03_pulse.wav	-29.02	-40.3	-29.33
58	13%	-41.33	female_list01_smile.wav	-23.14	-33.29	-23.27
59	13%	-41.5	female_list02_corpse.wav	-30.88	-41.67	-31.34
60	14%	-41.51	female_list03_class.wav	-25.4	-37.38	-25.54
61	14%	-41.54	female_list06_sup.wav	-27.77	-43.71	-27.97
62	14%	-41.6	female_list07_sag.wav	-31.07	-36.07	-31.68
63	14%	-41.61	female_list05_mast.wav	-28.98	-34.16	-29.35
64	14%	-41.77	female_list04_starve.wav	-26.61	-37	-26.78
65	15%	-41.85	female_list08_this.wav	-32.37	-40.74	-32.99
66	15%	-41.91	female_list08_us.wav	-26.34	-38.91	-26.49
67	15%	-42	female_list09_nuts.wav	-33.01	-32.03	-34.5
68	15%	-42.24	female_list06_slouch.wav	-25.61	-38.27	-25.74
69	16%	-42.67	female_list01_bask.wav	-23.28	-37.65	-23.34
70	16%	-42.68	female_list06_wasp.wav	-31.3	-36.89	-31.8
71	16%	-43.03	female_list09_mass.wav	-27.41	-30.36	-27.79
72	16%	-43.1	female_list01_feast.wav	-37.69	-37.41	-40.18
73	17%	-43.24	female_list08_chew.wav	-29.49	-32.93	-30.05
74	17%	-43.3	female_list08_rest.wav	-32.86	-36.79	-33.45
75	17%	-43.35	female_list10_plus.wav	-27.61	-39.73	-27.76
76	17%	-43.44	female_list05_curse.wav	-31.15	-37.23	-31.56
77	17%	-43.5	female_list06_hitch.wav	-31.19	-41.42	-31.58
78	18%	-43.66	female_list01_is.wav	-33.23	-30.73	-34.83
79	18%	-43.79	female_list05_pass.wav	-28.2	-39.46	-28.36
80	18%	-43.9	female_list06_as.wav	-24.28	-33.52	-24.38
81	18%	-44.11	female_list09_itch.wav	-30.94	-38.69	-31.35
82	19%	-44.15	female_list05_sly.wav	-29.88	-36.4	-30.15
83	19%	-44.32	female_list07_pounce.wav	-32.32	-36.45	-32.86
84	19%	-44.33	female_list02_gloss.wav	-28.53	-37.57	-28.74
85	19%	-45.38	female_list04_tick.wav	-32.72	-43.65	-33.03
86	19%	-45.4	female_list08_guess.wav	-31.37	-37.49	-31.7
87	20%	-45.61	female_list01_rise.wav	-24.21	-34.16	-24.29
88	20%	-45.66	female_list05_odds.wav	-27.69	-37.58	-27.81

89	20%	-45.7	female_list08_slide.wav	-27.07	-35.48	-27.19
90	20%	-45.75	female_list07_coast.wav	-36.04	-34.92	-37.47
91	21%	-45.83	female_list02_wish.wav	-30.12	-36.46	-30.45
92	21%	-45.84	female_list03_check.wav	-29.46	-40.64	-29.62
93	21%	-45.93	female_list02_ways.wav	-28.41	-34.15	-28.63
94	21%	-46	female_list02_pit.wav	-34.2	-35.92	-35.04
95	21%	-46.17	female_list01_use.wav	-29.22	-26.97	-30.89
96	22%	-46.5	female_list02_shoe.wav	-31.78	-32.72	-32.6
97	22%	-46.71	female_list07_quiz.wav	-33.17	-31.81	-34.44
98	22%	-46.75	female_list01_rat.wav	-29.62	-36.32	-29.85
99	22%	-46.76	female_list09_troop.wav	-33.1	-35.3	-33.83
100	23%	-46.91	female_list03_trip.wav	-33.37	-42.45	-33.69
101	23%	-46.91	female_list10_those.wav	-31.2	-33.07	-31.74
102	23%	-47.05	female_list03_rouse.wav	-26.35	-36.69	-26.42
103	23%	-47.1	female_list04_oils.wav	-30.45	-36.23	-30.69
104	24%	-47.15	female_list03_turf.wav	-30.48	-38.61	-30.67
105	24%	-47.24	female_list06_eyes.wav	-23.34	-33.56	-23.4
106	24%	-47.29	female_list09_ditch.wav	-32	-39.54	-32.29
107	24%	-47.5	female_list04_hatch.wav	-31.16	-44.8	-31.33
108	24%	-47.65	female_list06_raise.wav	-29.29	-33.46	-29.56
109	25%	-48.01	female_list06_clothes.wav	-31.67	-32.71	-32.24
110	25%	-48.08	female_list04_shed.wav	-29.48	-35.79	-29.66
111	25%	-48.12	female_list05_true.wav	-31.82	-31.57	-32.71
112	25%	-48.25	female_list10_ears.wav	-33.61	-33.29	-34.53
113	26%	-48.31	female_list08_chant.wav	-32.91	-37.75	-33.22
114	26%	-48.36	female_list04_shin.wav	-31.29	-31.56	-31.9
115	26%	-48.55	female_list04_touch.wav	-30.57	-39.45	-30.7
116	26%	-48.66	female_list09_arch.wav	-23.11	-39.61	-23.13
117	26%	-48.7	female_list01_wheat.wav	-32.29	-37.46	-32.61
118	27%	-48.75	female_list05_watch.wav	-26.31	-38.39	-26.38
119	27%	-48.75	female_list06_rooms.wav	-32.37	-27.25	-35.69
120	27%	-48.78	female_list10_etch.wav	-29.34	-40.47	-29.45
121	27%	-48.89	female_list09_fuse.wav	-34.84	-30.83	-37.51
122	28%	-48.91	female_list01_dish.wav	-32.2	-34.8	-32.69
123	28%	-48.95	female_list01_cleanse.wav	-29.56	-33.33	-29.83
124	28%	-49.1	female_list08_shack.wav	-31.17	-42.22	-31.3
125	28%	-49.12	female_list02_bought.wav	-31.81	-36.85	-32.14
126	29%	-49.14	female_list06_chart.wav	-21.99	-40.4	-22.01
127	29%	-49.16	female_list05_choose.wav	-36.76	-33.12	-38.97
128	29%	-49.18	female_list05_nose.wav	-30.6	-30.26	-31.2
129	29%	-49.19	female_list03_shout.wav	-31.24	-44.3	-31.35
130	29%	-49.2	female_list05_inch.wav	-32.35	-31.77	-33.37
131	30%	-49.28	female_list05_browse.wav	-28.14	-35.4	-28.26
132	30%	-49.38	female_list07_comes.wav	-34.28	-35.6	-34.81
133	30%	-49.39	female_list05_vase.wav	-25.63	-34.84	-25.7
134	30%	-49.52	female_list05_tug.wav	-23.56	-35.84	-23.61

135	31%	-49.53	female_list05_cheat.wav	-35.17	-37.92	-35.8
136	31%	-49.61	female_list07_shaft.wav	-29.73	-39.11	-29.83
137	31%	-49.75	female_list08_rot.wav	-31.33	-36.45	-31.54
138	31%	-49.88	female_list08_each.wav	-32.22	-36.68	-32.6
139	31%	-49.95	female_list10_bash.wav	-26.57	-37.93	-26.63
140	32%	-50	female_list02_trash.wav	-26.6	-39.12	-26.66
141	32%	-50.08	female_list06_eat.wav	-29.58	-30.11	-30.39
142	32%	-50.33	female_list05_owls.wav	-25.32	-35.86	-25.38
143	32%	-50.36	female_list05_shine.wav	-31.35	-32.66	-31.88
144	33%	-50.42	female_list03_thrash.wav	-27.57	-40.51	-27.61
145	33%	-50.45	female_list03_rate.wav	-30.15	-36.29	-30.31
146	33%	-50.51	female_list03_far.wav	-23.44	-37.47	-23.47
147	33%	-50.51	female_list09_flag.wav	-26.48	-35.51	-26.56
148	33%	-50.63	female_list01_plush.wav	-29.38	-40.33	-29.46
149	34%	-50.71	female_list07_chop.wav	-30.98	-43.02	-31.07
150	34%	-50.71	female_list09_fluff.wav	-26.15	-42.83	-26.18

Appendix 4. Instructions given to Participants at the time of the Localization Experiment

Instructions to participants

In front of you is an array of 13 speakers. From them noise and speech will be presented randomly. It is your job to identify which speaker you think the stimuli is being presented from. It can be quite tricky so in some circumstances you may need to use your best guess. Between each noise or speech stimuli I would like you to focus on the dot in front of you. After the speech or noise has finished playing I would then like you to turn and call out the number of the speaker you have identified and I will hear you through the intercom system. Try and be as accurate, but as fast as you can. Do you have any questions?

Appendix 5. Summary Graphs and Tables of the Pairwise Comparisons for Significant Post Hoc Interactions

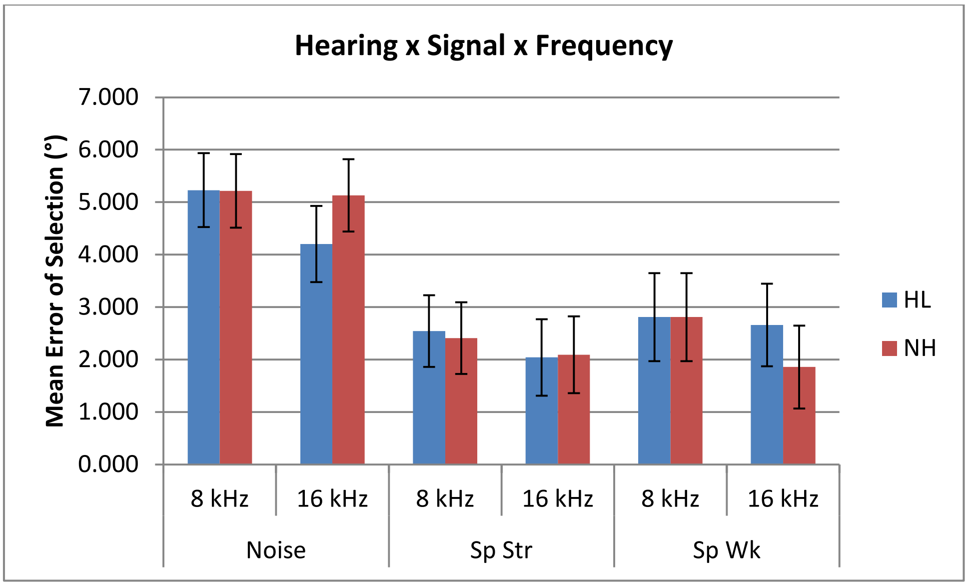
This appendix includes summary information from the post hoc pairwise comparisons for the significant results from the four-way ANOVAs for each of the four experiments in sequence.

For each significant ANOVA interaction, the pairwise comparison table produced by SPSS was produced and from this information summary graphs were produced for significant interactions. The graphs are included as they visually display the information from the tables that could otherwise be difficult to interpret. The y-axis is the mean error of selection (°) for the statistical groups being compared. For example the first graph for Experiment 1 compares Hearing x Signal x Frequency. There are three 'factors' being compared on the x-axis; hearing group (HL and NH), signal type (noise, speech strong and speech weak), and frequency (8 kHz and 16 kHz). In many cases, the x-axis is the location of the speaker of presentation. The error bars are the 95% confidence interval with Bonferroni adjustments for multiple comparisons for the lower and upper bounds for the means, which are approximately two times the standard error.

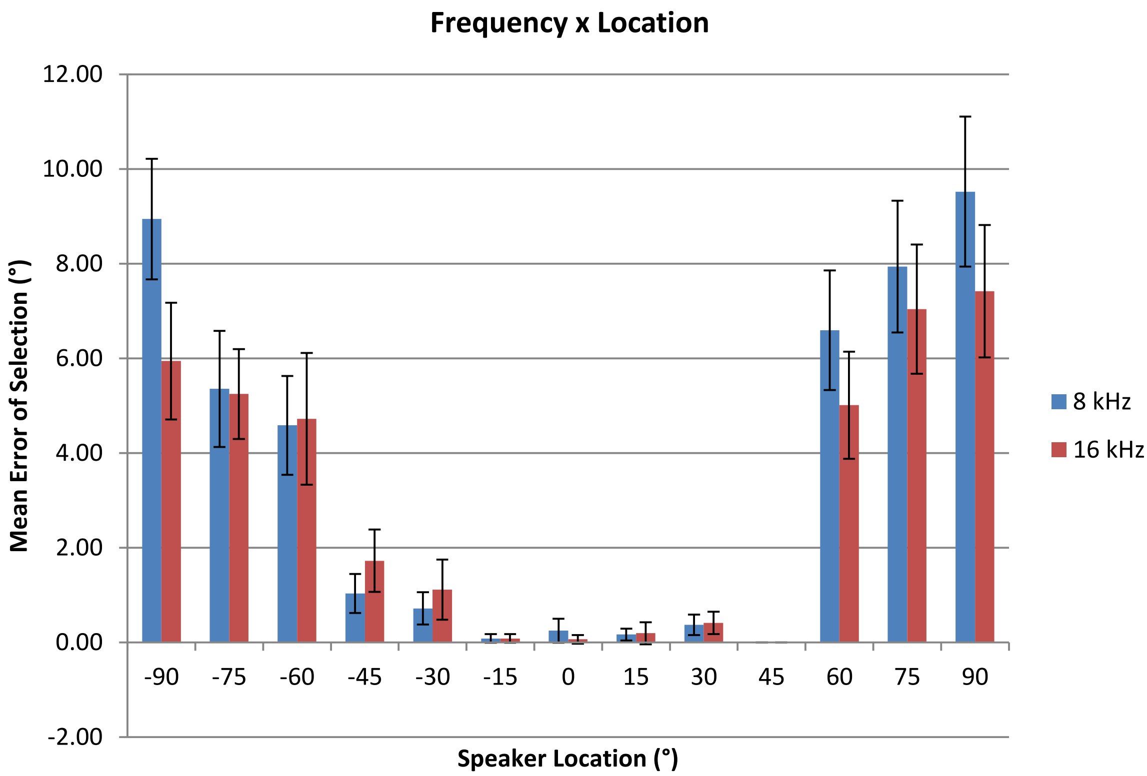
For two means on the same graph to be significantly different at the 95% level the mean for the second group needs to be outside the lower and upper bounds of the confidence for the first mean. For example from Experiment 1, Hearing x Signal x Frequency, it can be seen that where comparing the mean errors of selection for HL and NH for noise 16 kHz that the mean error of selection for the NH result is outside of the 95% confidence interval for the HL result and therefore these two means are significantly different ($p < .05$). Where the significant difference between means are reported in the results section, the p-value of the confidence interval is quoted; for example it was found the mean A was greater than mean B ($p < .05$).

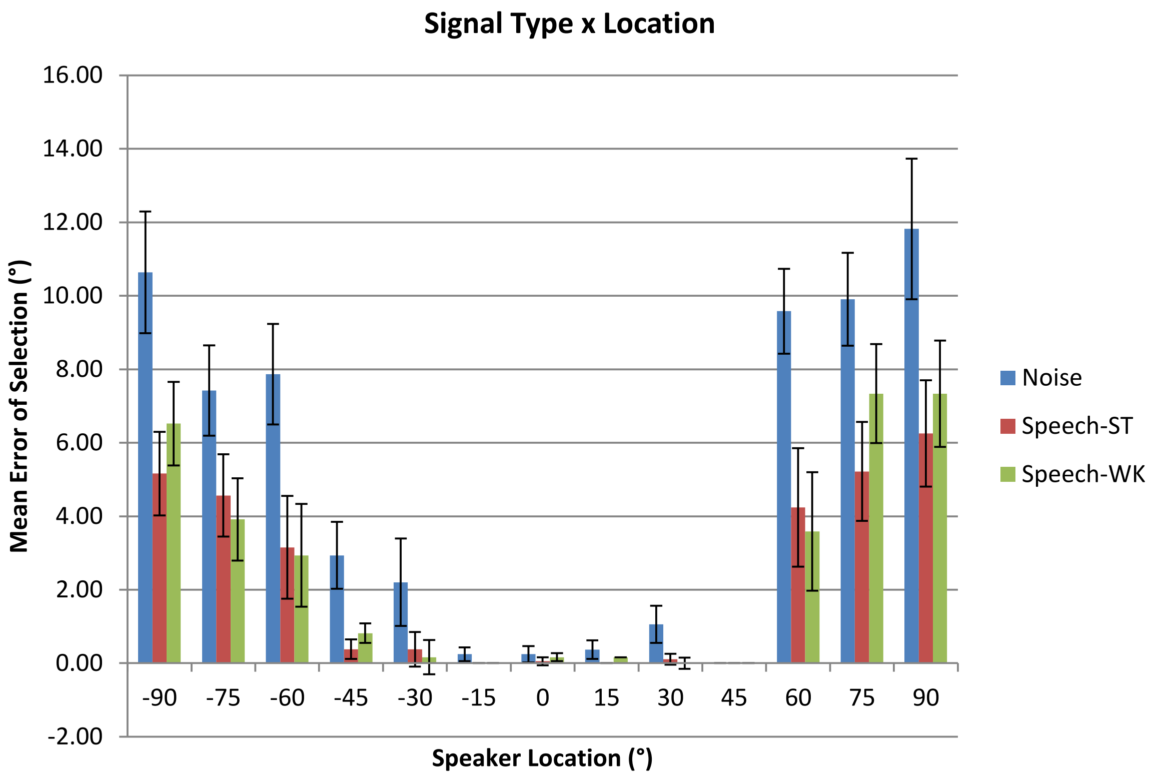
Experiment 1. Frontal Horizontal Plane

Hearing x Signal x Frequency



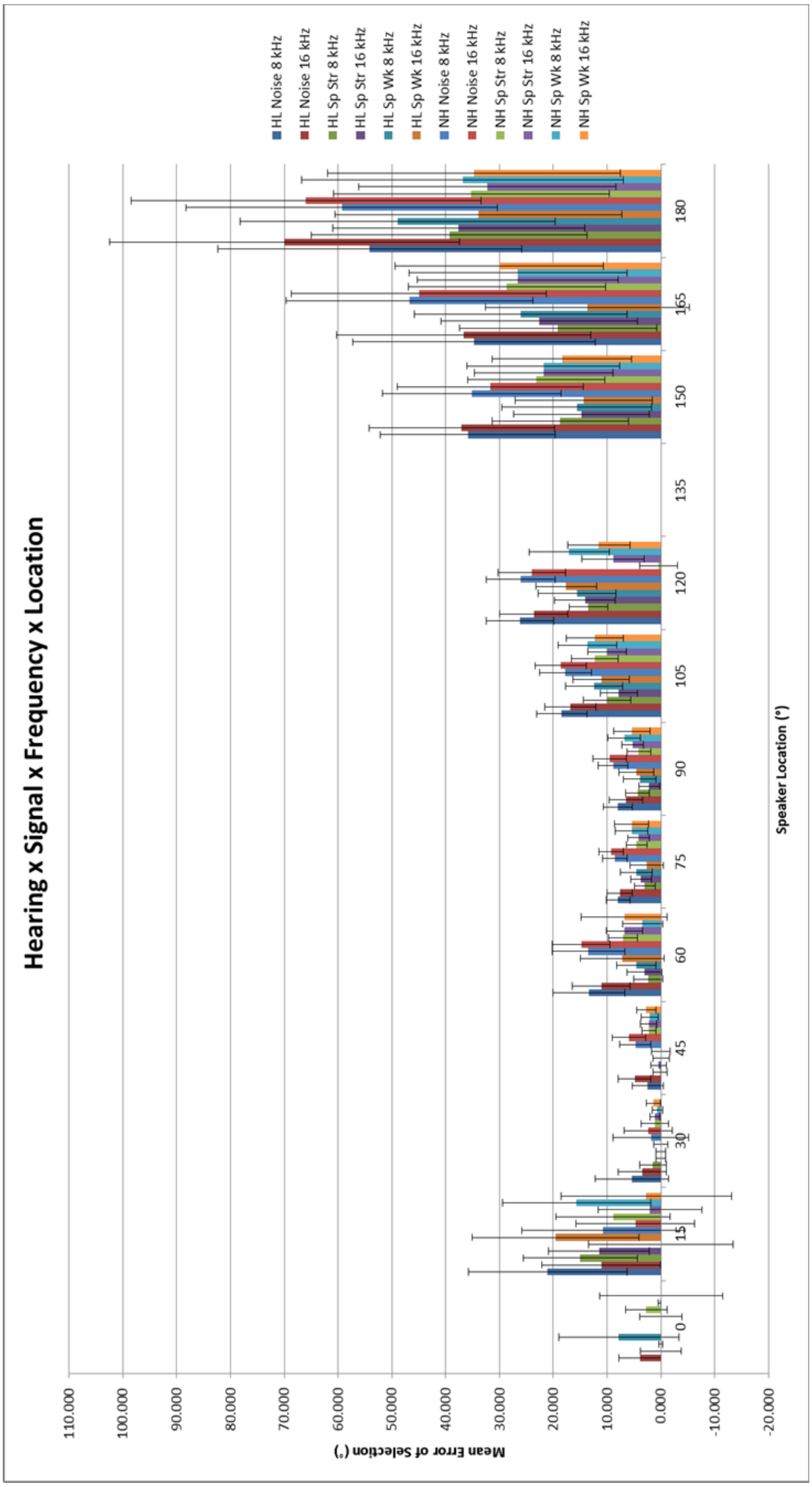
Frequency x Location




Signal Type x Location
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
Mean Error of Selection (°)
-90
-75
-60
-45
-30
-15
0
15
30
45
60
75
90
Speaker Location (°)
Noise
Speech-ST
Speech-WK

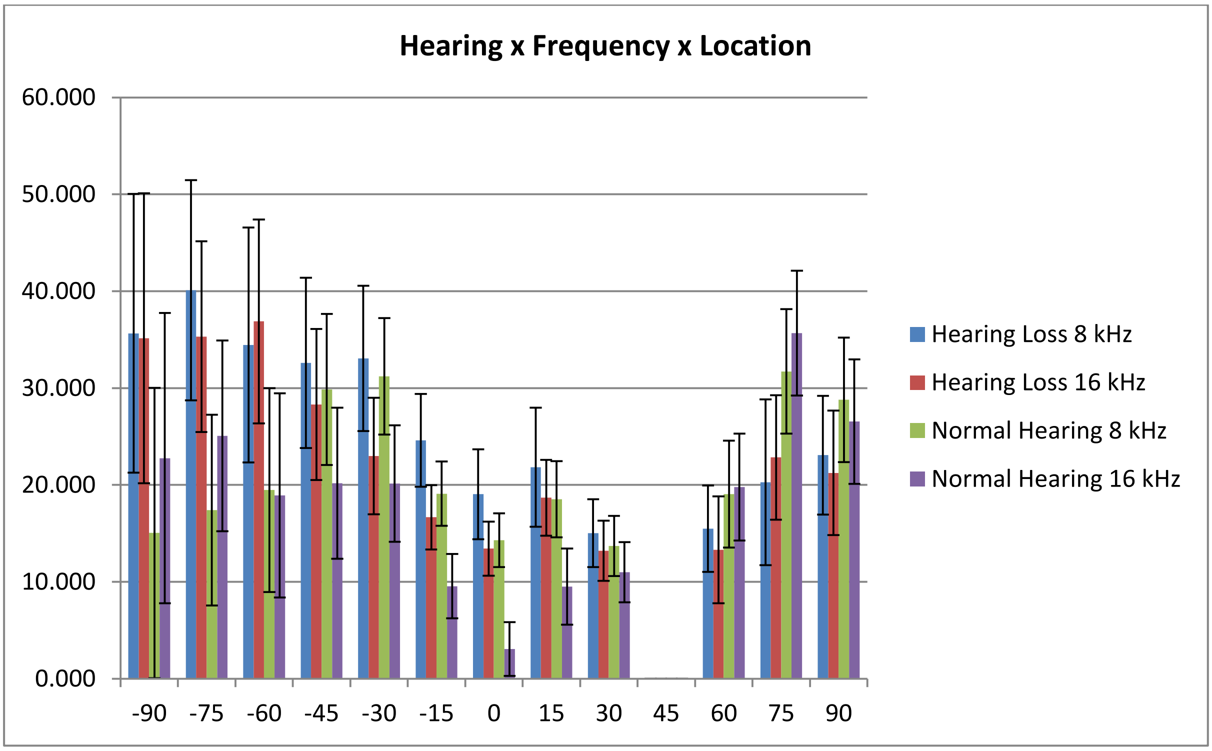
Experiment 2. Lateral Horizontal Plane

Hearing x Signal Type x Frequency x Location



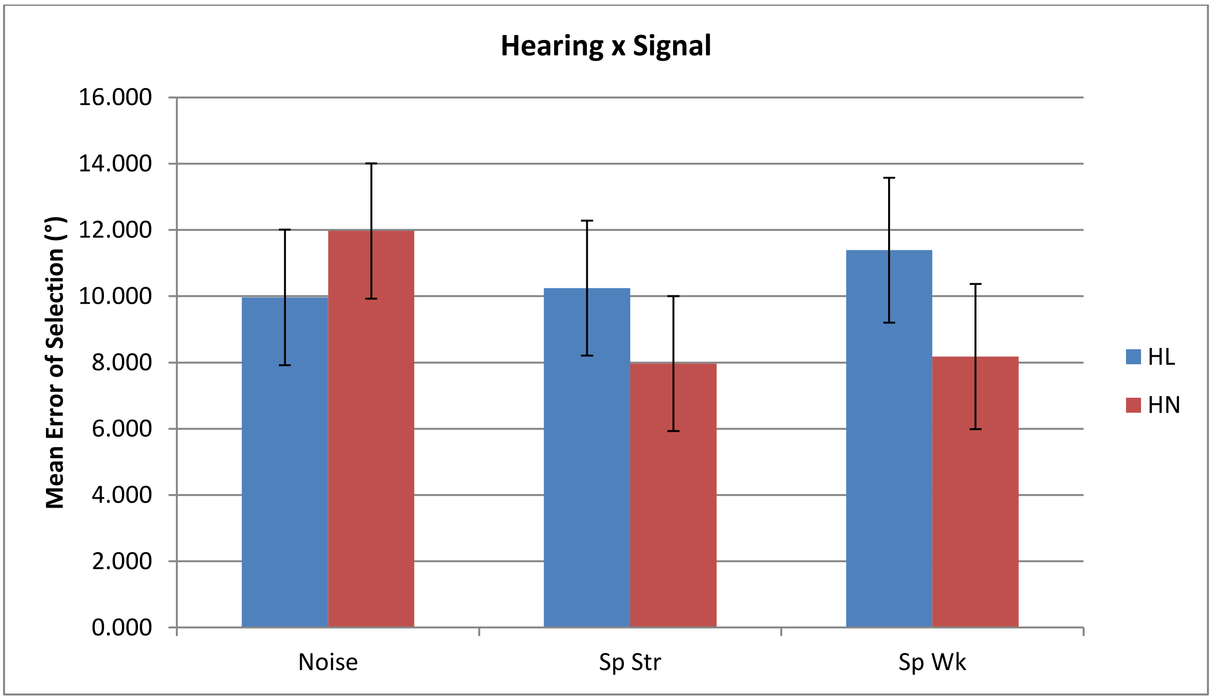
Experiment 3. Frontal Lateral Plane

Hearing x Frequency x Location

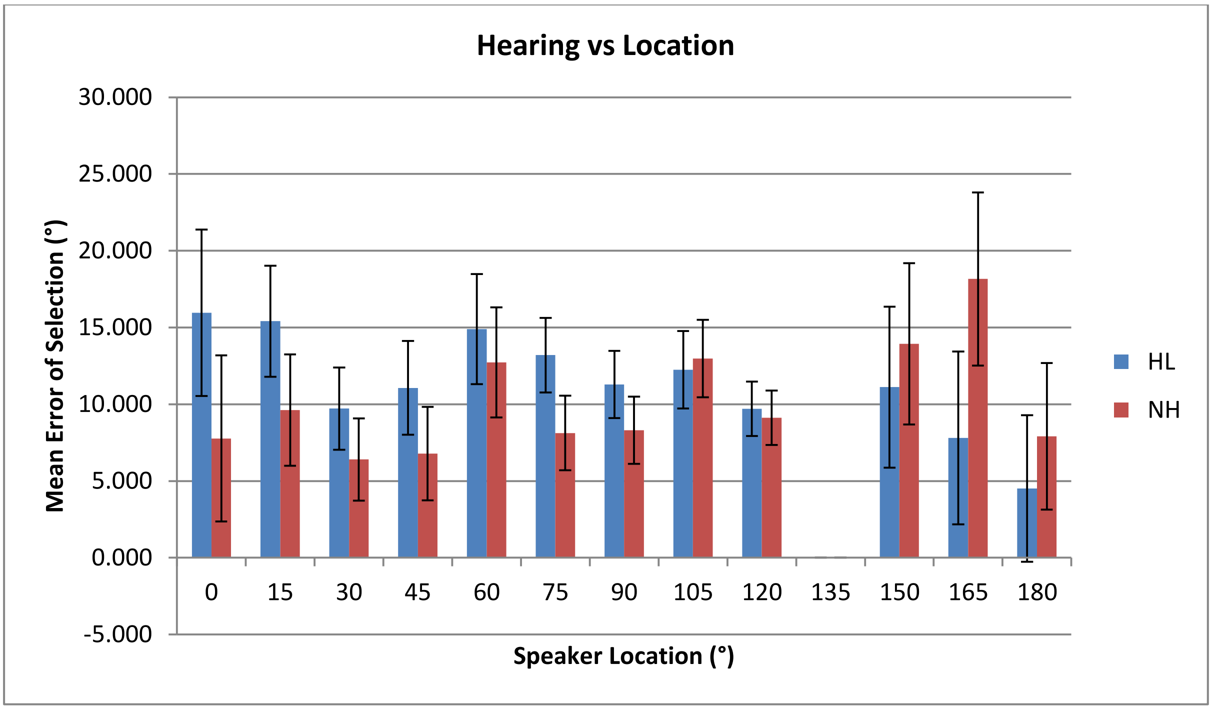


Experiment 4. Lateral Vertical Plane

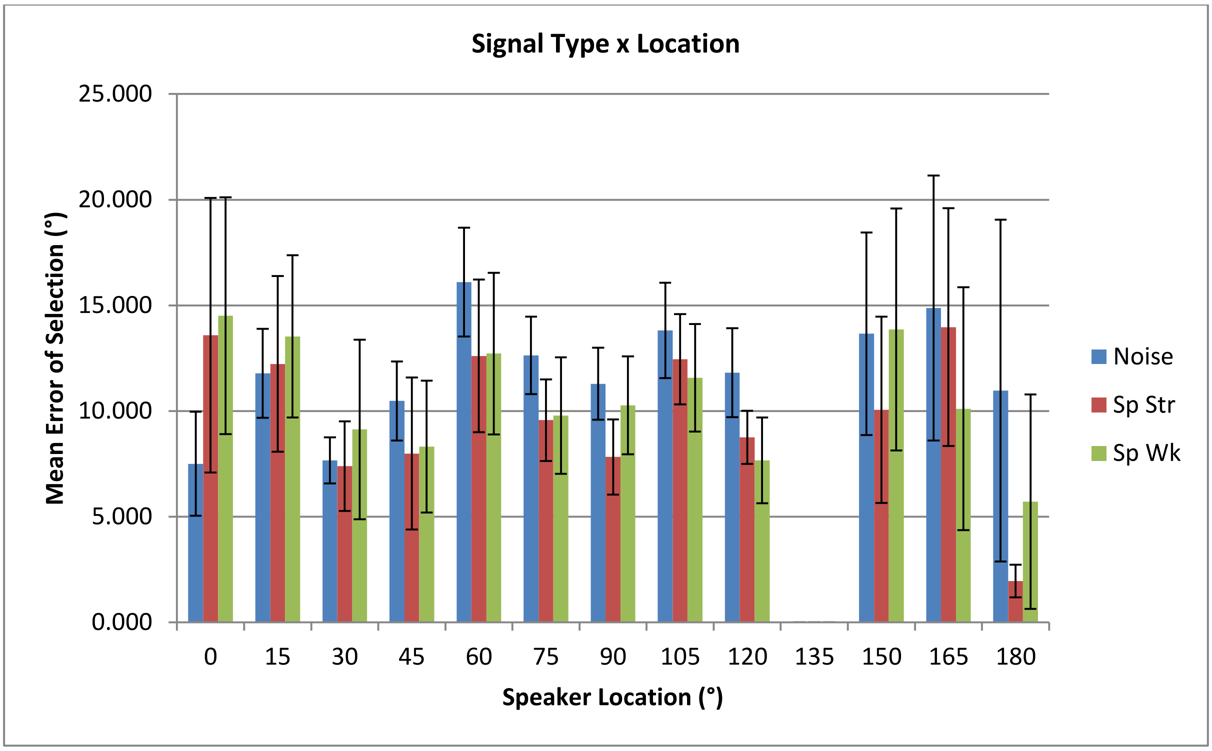
Hearing x Signal Type



Hearing x Location



Signal Type x Location



Frequency x Location